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SOUNDING OF THE ATMOSPHERE USING BROADBAND EMISSION RADIOMETRY (SABER) OBSERVATIONS OF POLAR WINTER CONDITIONS IN 2009; COMPARISONS WITH YEARS 2002-2008

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Interim Report

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14. ABSTRACT This report summarizes results from eight years of observations of northern polar winters by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite, with a specific focus on the year 2009. That winter, like all but one since the TIMED launch, featured an extraordinarily intense stratospheric sudden warming (SSW). We have documented its effects on stratospheric and mesospheric temperature, and on the OH layer in the upper mesosphere, and compared them with those in other years—particularly 2006, which had a very similar SSW. We show that mesospheric cooling accompanied each SSW, but with varying altitude ranges, durations, and overall effect. Cooling in the upper mesosphere, when it could be discerned, preceded both the SSW and the cooling at lower altitudes by a few days. Years 2004, 2006, and 2009 stood out with extraordinary disruptions of the mesospheric temperature structure, and very low bright OH layers, in the weeks after the SSWs. Year 2008 featured four separate weaker but remarkably consistent warmings. We also looked for, but could not confirm, signs of remote SSW influences in the equatorial region.						
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1. INTRODUCTION

This Interim Scientific Report describes work that was undertaken by ARCON Corporation according to the provisions of contract #FA8718-04-C-0031. Much of this work was done during the fifth year in which it was in effect, that period being 1 August 2008 through 31 July 2009. One purpose of the report is to document observations made by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument [1] on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite prior to, during, and following the very strong stratospheric sudden warming (SSW) that took place in January 2009. Another is to compare and contrast these observations with those from preceding boreal winters, most of which were also characterized by one or more SSWs.

2. BACKGROUND

Stratospheric sudden warmings (SSWs) are high-latitude wintertime occurrences, seen with some regularity in the Arctic but quite rarely over Antarctica, that comprise severe disruptions of the thermal and dynamical structure of the polar atmosphere. Normally, the polar winter stratosphere is cold, and circumpolar winds form a vortex that isolates air in the region and inhibits exchange to lower latitudes. When an SSW occurs, its signature is a rapid increase in temperature in the upper stratosphere, followed over the course of a few days by warming at successively lower altitudes, down to the lower stratosphere. At the same time, prevailing eastward winds are disrupted and the vortex becomes distorted, offset from the pole, and/or split into pieces.

SSWs were first identified nearly sixty years ago [2] and have been studied ever since. The onset of an SSW is said to take place [3] when zonal mean temperature, at or below 10 mb (~30 km), is first seen to be increasing as one moves from 60^o toward the pole; e.g. when the normal latitudinal gradient of temperature in the stratosphere reverses. A major warming occurs if the zonal mean zonal wind also reverses direction, turning from eastward to westward. SSW climatologies have been constructed to classify them, summarize their characteristics, and study their life cycles [4,5,6]. Major warmings occur irregularly, with a long-term average of about one every two years, most frequently in January or early February. Minor warmings are more common.

Current understanding of the causes of SSWs focuses upon the role of planetary waves (PWs) in forcing the most dramatic changes. Matsuno [7] first studied this aspect of the issue quantitatively, and more recent work has greatly refined the picture without overturning the basic ideas presented by him. A very succinct summary of those ideas is as follows. It is known that upward- and poleward-propagating planetary scale waves occur fairly regularly in northern hemisphere winter and are viable in the presence of eastward-directed winds (westerlies). The higher they go, the larger their amplitudes become. Then, assuming a normal winter vortex, a natural consequence of the existence of such waves is a certain deceleration of the eastward polar night jet. When there is unusually strong activity, waves may reach into the upper stratosphere, with amplitudes sufficiently large to cause the wind not only to decelerate but to actually reverse and become westward. When this happens, a critical layer forms, propagation is no longer possible, and wave energy is released to the atmosphere in the form of heat. If PWs continue to impinge upon the region, deceleration of wind and deposition of heat occur at successively lower altitudes, producing within a few days a downward-propagating warming, to the extent of tens of Kelvins. Thus, as a result of the interaction of persistent strong planetary waves with the prevailing zonal wind, the polar stratosphere becomes a sink for a vast amount of energy from lower altitudes and lower latitudes.

Indeed, subsequent research has revealed that conditions influencing the development of SSWs, as well as conditions influenced <u>by</u> them, are global in scale and not limited to the stratosphere. Much work has focused upon the tropospheric forcing, for example the role of blocking systems (large-scale, quasi-stationary, high-pressure systems that may steer PWs up into the vortex region), which appear to be necessary but not sufficient for producing SSWs [8,9]. It has also been recognized that disruptions of the stratosphere may in turn perturb the troposphere and even affect surface weather. In early February 2009, London received heavy snowfall for the first time in two decades—an event attributed to the disruption of the jet stream that accompanied the SSW of late January [10].

However, our present interest is in aspects of stratospheric sudden warming events that are related to higher altitudes (mesosphere) and lower latitudes. Matsuno's early paper [7] recognized that mesospheric cooling should accompany SSWs, as a result of concurrent upward flow above the altitude of the initial warming. Much more recently, Liu and Roble [11] used the Thermosphere Ionosphere Mesosphere Electrodynamic General Circulation Model, (TIME-GCM) to elucidate details of the process, showing in particular that the weakening or reversal of the stratospheric winds permits an increased flux of gravity waves (GWs) into the mesosphere [12], having phases such that the momentum they impart to the atmosphere when they eventually break produces an equatorward meridional flow at high altitudes, hence upwelling and cooling in the mesosphere. These calculations also predict that the cooling should begin two weeks prior to the peak stratospheric warming, implying that weakening—as opposed to reversing—the vortex winds is a sufficient condition for initiating it.

Rocket observations up to ~75 km [13,14] confirmed the existence of such cooling, as did lidar measurements extending a little higher [15]. Still higher, OH rotational temperature measurements produced further evidence of mesospheric cooling (tens of Kelvins), but with ambiguities regarding its timing relative to the SSW. For example, Myrabø et al [16] observed a 1-2 day delay with respect to the maximum warming, while Walterscheid et al [17] found that the onset of cooling preceded the 1993 minor warming by many days, and Sigernes et al [18] reported cooling at varying intervals prior to and during three SSWs for which they had coincident data. Thayer and Livingston [19] used OH and lidar measurements to detect a substantial mesospheric cooling that, according to them, preceded a regional disturbance, making the point that disruptions other than SSWs are sufficient to produce such wintertime cooling. In that case, however, <u>local</u> stratospheric temperatures did vary in a fashion resembling an SSW.

Later, Siskind et al [20] used temperatures from an early SABER retrieval version (v1.04) to study the entire polar mesosphere during three SSWs, including the only major one ever seen in the southern hemisphere. They found a pronounced anticorrelation in temperature between mid stratosphere (10 hPa) and mid mesosphere (0.1 hPa), but not between mid stratosphere and the upper mesosphere (0.01 hPa), and concluded that the OH layer may be too high to capture the full extent of mesospheric cooling. Cho et al [21], on the other hand, did find marked cooling at the OH level at the time of the SSW of 2001. Also, there was a precursor <u>warming</u> there—but not a few km higher where O_2 emissions originate. This led them to remark that meridional inflow must have been occurring in the intervening altitude range prior to the SSW but below the

OH layer during it, in order to produce the observed temperature changes by changes in adiabatic heating or cooling. None of this addressed the issue of the actual altitude of the OH layer, which has been shown to vary substantially in wintertime [22].

From these observations, the original prediction [7] that mesospheric cooling correlates with stratospheric sudden warmings appears to be on solid footing, even as questions remain about the timing, altitude regime over which it occurs, and associated flow.

Somewhat less certain are cause/effect relationships between SSWs and lower-latitude phenomena. Early isolated observations suggested the existence of correlations between stratospheric temperature anomalies in the equatorial and polar regions in SSW winters [14], with equatorial cooling of a few degrees in the upper stratosphere accompanying the peak polar-region warming and persisting thereafter for many days. Since that time, many papers have explored this and other links to remote regions, including recent ones with data from the tropical station at Gadanki (13ºN). These show upper-stratospheric warming a week or so after the SSW in 2001 [23], and coincident with the SSW in 2006 [24]. In both cases cooling in the equatorial middle mesosphere was also reported. M. Shepherd et al [25] investigated the latitude range 5º-15ºN using temperature and wind data from several sources during three winters with SSWs (two minor), obtaining similar results. Kodera [26], on the other hand, using a composite set of global measurements from twelve SSW periods, found cooling in the equatorial lower stratosphere and upper troposphere that is associated with increased convective activity (and is not symmetric about the equator), attributing it to changes in meridional circulation and describing it as an effect rather than a possible cause of the SSWs. He also reported differences in zonal winds in the extratropical southern hemisphere.

Further work on interhemispheric connection was prompted by observations [27] showing that the prevalence of noctilucent clouds (NLCs)—a proxy for cold temperatures in the summer polar mesosphere—is negatively correlated with the temperature of the polar winter stratosphere. An exercise using the Canadian Middle Atmosphere Model [28] then revealed that increased planetary-wave activity in the winter stratosphere, which results in warm anomalies in temperature there, also produces a somewhat warmer summer polar mesosphere ~10-20 days later. The idea is that altered GW fluxes modulate mesospheric meridional flow, affecting zonal winds in the summer hemisphere and hence GW drag near the opposite pole. (Conversely, reduced activity results in a somewhat cooler mesosphere there.) The strongest wintertime PW activity is associated with SSWs, but according to this study such effects may be also seen with weaker or less prolonged disturbances [28].

Very recently, Dyrland et al [29] published an interesting study that correlated variations in mesospheric meridional winds at Longyearben (78ºN) with other characteristics of the upper mesosphere—including temperature and OH layer characteristics—prior to and during the very strong SSW of January 2004. These characteristics (not winds) had previously been studied by us [22,30] for that period and also for the SSW of 2006, using SABER data. They included extremely low and bright OH layers, and unusually high temperatures at the altitude of the OH layer and in the mesosphere in general, and were explained by us (in part) by greatly enhanced downwelling in the days and weeks following the peak stratospheric warming [22]. The new work [29] supports this conclusion. It shows explicitly that equatorward (poleward) winds, which are unambiguously associated with upward (downward) vertical flow in the polar regions, correlate with cold (warm) OH rotational temperatures and with SABER temperatures. During the 2003-2004 winter, meridional wind reversals were observed at different times, each time correlating with changes in T and the OH layer. Strong poleward flow following the SSW is then seen to be responsible for (1) transporting atomic oxygen from equatorial source regions; (2) inducing adiabatic heating; and (3) enhancing downward transport of O from the thermosphere, which further heats the mesosphere through the chemical reaction that produces OH [31,32].

Finally, we comment very briefly on the association of SSWs with the solar cycle (SC) and the quasi-biennial oscillation (QBO). Labitzke and van Loon [33] summarized a lot of the work that had been done up to that time using data from three SCs, pointing out that major SSWs preferentially appear in the west phase of the QBO during solar max, in the east phase during solar min, and not at all during the west phase at solar min. Countless papers followed, analyzing the relevant issues. Among them was one [34] that, using complicated statistical analysis, seems to show that the SC is "responsible" for a substantial warming (~7 K) of the polar winter stratosphere relative to the coldest, least perturbed state (west QBO, solar min) identified previously. Then, however, major stratwarms appeared in both 2007 and 2009, during the west phase near a historically low solar minimum. In fact, the one in 2009 was the strongest and most prolonged ever observed [35]. It thus represents an "extreme outlier" [36] and invites further study of this already-well-studied topic.

In fact, the surprising appearance of the 2009 stratospheric sudden warming and some of its similarities to the episodes of 2004 and 2006 are only a part of what prompts this study. Having published observations [22] of extremely unusual conditions in the mesosphere in those two years, in each case subsequent to a major SSW—and then observed another major stratwarm in 2008 that produced no extreme anomalies—the need to document SABER observations of northern hemisphere (NH) winter for as many years as possible had already become apparent. This report addresses some of that need.

3. SABER OBSERVATIONS

3.1 Overview

In the past, investigations of SSWs have mostly relied upon meteorological data sets and, for higher altitudes, observations at specific locations. But the need to expand the range of study to the global atmosphere has become apparent. SABER is an excellent tool for this purpose, because it comprises the only global data set with retrieved temperature that reaches mesopause altitudes and beyond.

SABER has been collecting data continually, on a near-global basis, since early in 2002. The instrument has been described by Russell et al [1], and details concerning data collections that pertain to our particular needs have been outlined before [30,37]. This work mostly involves atmospheric temperature and emissions from the OH radical, the latter being reported as volume emission rates (VERs). We simply reiterate here that temperature is retrieved into the lower thermosphere from CO_2 longwave emissions using a non-LTE algorithm [38] that we helped develop; and that the VERs are derived, using an Abel inversion, from two sets of radiances originating in $\Delta v=2$ bands of OH. The so-called OH-B emissions that include the 5-3 and 4-2 bands at ~1.6 µm are what we use for most of our analysis; VERs from the OH-A bands (~2.0 µm, originating in the v=9 and v=8 states) give similar results. "Unfilter factors" [39] account for the fact that the interference filters do not fully span the wavelength range of the OH emissions. We used retrieval version 1.06 for years 2002 through 2005, and version 1.07 for other years. The differences between these versions are expected to be negligible for polar winter conditions

[40,22], a fact we checked by completing our work with year 2006 data using both versions. Data reported here are from SABER "north-viewing" yaw cycles, from mid-January to mid-March, when latitudinal coverage is approximately 51ºS to 83ºN. Prior to mid-January each year, the view is ~83ºS-51ºN, so the instrument does not see the early northern winter at the highest latitudes.

According to a compilation of the Meteorological Institute at the Free University of Berlin [41], major stratospheric warmings have occurred in each NH winter monitored by SABER through March 2009, except for 2004-2005. Dates assigned to major SSWs are supposed to be those on which the zonal mean zonal wind at 60ºN reverses, but there seems to be some ambiguity in the literature about what those dates actually are. Table 1 lists dates of recent events, as best we could determine them, and those of some minor warmings as well. It also records the QBO phase and approximate solar activity level. "DOY" refers to the day of the year. All figures and tables are found in the Appendix.

Of the twelve events listed in Table 1, only the major SSW of 2004 occurred prior to the middle of January. As such, it (and preceding days) was the main period of interest that was not observed by SABER. That SSW and the one in 2006 were very strong events that produced large anomalies in the polar mesosphere, first documented by us [22,30]. These include, prominently, the low, bright OH layers mentioned earlier and a remarkable distortion of the temperature structure, which resulted in a very cold region at ~35-50 km and a "stratopause" as high as ~75 km with temperatures approaching 280 K. All of this occurred after the SSWs themselves, and in both cases these conditions persisted for several weeks. The event of 2009 was also very strong. It produced similar effects, as will be seen in the data presented below. These three SSWs are undoubtedly the most intense ones since at least 1987, if not since the phenomenon was first identified in 1952.

Other SSWs that occurred during SABER's watch failed to have such dramatic effects on the polar mesosphere. In view of the paper by Dyrland et al [29], which associated the anomalous events of 2003-2004 with changes in meridional circulation, and in view of the role of the meridional circulation in producing the normal polar winter temperature structure, it is interesting to us to consider the possibility that there may be a continuum of perturbations in the polar mesosphere, associated with SSWs or perhaps not, that in other winters might induce less spectacular but nonetheless consistent changes that could be observable with SABER data. We will not attempt to finalize an answer to this question, but the data presented in this report are certainly necessary to consider.

3.2 Temperature

Figures 1A and 1B show the daily zonal mean temperature as a function of altitude, for a far-north latitude band throughout the north-viewing January-March yaw cycles of the last eight winters. In the lower-left hand corner of Figure 1A(a) one sees a classic picture: the downward progression of warm temperatures in the stratosphere accompanying the 2009 SSW. Initially, on 12 January, the wintertime stratopause was above 50 km and was quite warm (~265 K), while the lower stratosphere was colder than 200 K. After a few days, the situation changed abruptly, with the upper stratosphere cooling and the lower stratosphere warming. The date assigned to this SSW is either 21 January [35] or 24 January [36], and by those dates temperatures exceeded 270 K over much of the middle stratosphere. The region cooled once again at the beginning of February, and concurrently the stratopause suddenly reformed above 80 km. It remained in place near this altitude for several weeks, with temperatures reaching ~255 K, and then descended gradually in the latter part of February and early March. The stratopause was still above 60 km, and the adjacent warm region very broad, when the SABER instrument reverted to its south-viewing orientation on 15 March.

One sees much the same thing in Figure 1A(d), which documents the 2006 SSW and subsequent disruption of the middle atmosphere. In that year, the stratopause was a little lower to start, and the initial warming a little less intense—according to these data, at least—but the dates at which the transitions occurred are almost the same and the behavior in general is very similar. In considering whether one event or the other was the "stronger" one, it is useful to keep in mind that zonal means by definition mask the variability that occurs around each latitude band. In fact, the 2009 disruption in the mesosphere tended to be quite symmetric in the aftermath of the SSW, e.g. there was rather little variation with longitude, in distinct contrast to 2004 and 2006. [22].

Figure 1B(f) shows the aftermath of the SSW that occurred on ~2 January 2004, two weeks before SABER observations began. By the middle of the month, the high stratopause had already formed and begun its descent, which was very gradual but continuous throughout the ~60 days of measurements. Other than this slow pace, and the longer period of very cold temperatures in the ~30-40 km region (the tropopause?), that year seems quite similar to the other two. Evidently the longest-lasting phenomenon related to SSWs is the mesospheric disruption that follows in the aftermath of some of them.

The other plots in Figures 1A and 1B, taken individually and/or in contrast to the three we have already discussed, reveal the variability that is well known to occur in NH winters. In 2008, Figure 1A(b), one finds clear signatures of the four SSWs listed for that year in Table 1. In fact, the first two—which are listed as minor—appear in these plots to be the most intense, with the major warming on 23 February (day 54) being distinctly less impressive. Mesospheric cooling is apparent in each case. There even is a fifth pulse of warming at the beginning of March, with associated cooling above. It is interesting to note that at about 110 km there seems to be a warming effect correlated with each mesospheric cooling. Timing aside, this is actually in accord with certain model predictions [11]. SABER temperatures at that altitude have very large error bars, however, so even daily averages like these must be viewed cautiously.

Note, the nominal dates of the minor warmings in 2008 are those on which the meridional temperature gradient reversed. In the case of the second event, that occurred ~5 days before other effects became manifest in the data of Figure 1A(b), in those of the original study [42], and in other data we present below. We have concluded that the appropriate date for this event should be day 38 (7 February), rather than day 33.

The stratwarm of 2007 was in February [41]. It is not apparent, from the stratospheric temperatures alone, whether it occurred near day 36 or day 55, although it is probably the latter. Day 55, or 24 February, also seems to have a weak mesospheric cooling near 70 km. In addition, it appears that there were rapidly-alternating periods of (slightly) warmer and cooler air at ~80-85 km for much of the winter.

Like the winters preceding and following it, the winter of 2005, Figure 1B(e), was remarkable as well, but for a different reason. Instead of being warm like many of the others, the lower stratosphere was the "coldest on record" [43]. However, the stratopause region near 50 km was quite warm, with temperatures hovering near 260 K for most of the period observed by SABER. The upper mesosphere was relatively cold throughout. Among the eight late winters documented here, 2005 seems to have had the least week-to-week variability—perhaps because of the strong lower-stratospheric vortex, which persisted until early March.

In Figure 1B(g) one can see the signature of the SSW of 16 January 2003 as a warming right at the beginning of the SABER yaw cycle, with mesospheric cooling at ~65 km that appears to have lagged by a day or two. There is also evidence of a fairly abrupt warming at ~80 km, where the temperature increased by ~30 K over the course of a few days. This is suggestive of the behavior during the 2006 and 2009 winters, when the stratopause actually reformed at that altitude following those very strong SSWs. But in 2003 there was no continued development in the following weeks; despite considerable subsequent temperature variability in the lower mesosphere and upper stratosphere, the stratopause remained at much lower altitudes. Signs of the "nearly major" [44] warmings of 19 February and 5-6 March are difficult to discern in these zonal-mean data.

Finally, in 2002—despite a less complete data set—Figure 1B(h) clearly depicts the SSW of 17 February, day 48, with associated cooling at ~70 km and a brief spot of warming (~20 K) above that. Over a period of nearly two weeks, the stratopause dropped by about 12 km, but thereafter it rapidly reformed and remained above 50 km.

We made plots of SABER temperature in other 6-degree latitude bins, down to latitudes of ~54ºN or below. Those documenting the 72-78ºN range are all very much like the ones in Figures 1A and 1B. That is, the periods of warming or cooling, the altitudes at which these appear, and the variations in general occurred at the same time and with nearly the same magnitude. During the years 2005 and 2007, this was also true down to much lower latitudes. The main difference in those years was that the stratopause temperature—which did not change very much in 60 days at any latitude—was lower at the lower latitudes. This was also so in 2008, except the manifestations of that winter's warmings did become more diffuse further south (see below).

Since one of our purposes is to document the remarkable 2009 SSW, it is worth showing how the zonal mean temperature varied with latitude in that year. Figures 2(a) and 2(b) give the temperature in the 66-72ºN and 54-60ºN bins, respectively, for comparison with Figure 1A(a). By the same token, 2008 was a year with several warmings, and each can be associated with perturbations in the mesosphere (albeit of quite different extent). This makes it worthwhile to display some of the latitudinal variations in that year as well, which we do in a similar fashion in Figure 3 for comparison with Figure 1A(b).

One of the remarkable things about the SSW of 2009—and perhaps the reason it has been labeled "record-breaking" [35]—is the latitudinal extent of the disruptions it visited upon the stratosphere and mesosphere. Figure 2(a) shows warming in the stratosphere in mid-January that was every bit as intense as at higher latitudes, with concurrent mesospheric cooling. A week thereafter, warming occurred in the mesosphere, although not as intensely as farther north, and the stratopause briefly reformed near 80 km. Even south of 60ºN, Figure 2(b), the same clear manifestation of the SSW can be seen in the stratosphere in mid-January. At those latitudes, concurrent and subsequent changes in the mesosphere were less pronounced but nonetheless recognizable.

By way of contrast, manifestations of the 2006 SSW were considerably diminished in the 66-72ºN bin (not shown) compared to the highest latitudes, and even more so further south. There, the region of intense warming was restricted to the upper stratosphere—there appears to have been little or no descent—and although the stratopause disappeared in late January only to reform in the mesosphere a week later, it was much cooler (~20 K) and lower (~5 km) than at the highest latitudes.

Most effects of the minor and major warmings in 2008 are apparent in the 66-72ºN latitude range, Figure 3(a), but as in 2006 they were somewhat diminished relative to those farther north. Warming in the stratosphere was less intense, and the minor warming of 16 February can barely be discerned in the stratosphere or mesosphere. Except for that, the quasi-periodic cooling/warming in the mesosphere occurred in the same pattern as at higher latitudes, but with excursions of ~25 K rather than ~40 K. Yet farther south, in the 54-60ºN range, events in the stratosphere were reduced to pulses of slightly elevated temperature, and the third one had disappeared altogether. Mesospheric temperature shifts are still apparent.

3.3 OH Layer Characteristics

Figures 4A-4H summarize, as succinctly as we can do it, the properties of the OH layer during eight NH winters, 2002-2009, in reverse order (2009 first). Each figure shows zonal mean quantities over the latitude range north of 52ºN, for the duration of each ~60 day yaw cycle. These are (top) the layer altitude; (middle) the peak VER; and (bottom) the retrieved temperature at the layer altitude, although the retrieved temperature has not been plotted for several of the years. These quantities were calculated by (1) locating, for each valid SABER event, the altitude at which the maximum value in the OH-B VER profile occurs; (2) recording the VER there; (3) recording the temperature there; and (4) averaging these quantities over three-degree latitude bins and 2-day observation periods. "Valid" events are those for which the solar zenith angle (SZA) was greater than 105º and the shape of the VER profile was such that the peak could be located unambiguously. The algorithm for eliminating profiles with double peaks and other problematical features was described previously [30].

[An alternative approach for locating the layer altitude is to weight it by the VER and calculate the mean value. The same can be done for temperature. This is preferable for comparing temperature results with those of zenith-looking instruments, but not necessarily for compiling global statistics. For both altitude and temperature, this changes the zonal means a little bit. For example, it makes the layer altitude systematically ~1 km higher than when the location of the peak VER is used, because the OH layer is generally not exactly symmetrical about the peak. Since we are studying changes occurring during the winter, it doesn't make much difference whether or not we use such a "brightness-weighted" algorithm, but the slight differences are worth noting. In this context, we note that the altitude of the OH-A layer, calculated either way, is also systematically higher than that found from OH-B. This is because of the effect of altitude-dependent quenching on emission from different vibrational states.]

The feature of all eight of these figures that immediately strikes the eye is the correlation among the layer altitude, VER, and layer temperature in each year. One sees that when the OH-B layer altitude was low, the VER and the layer temperature were high, and conversely when the layer was high the VER and temperature were much lower. If one makes scatterplots with these quantities, comparing any two of them for large sets of events, one finds correlation coefficients greater than 0.9 (in magnitude). The correlations, which are at least partly the consequence of the variability of vertical winds, have been discussed in the literature [22,45]. Since they have also been noted extensively in an earlier report of ours [30], at least for the year 2004 and 2006, we will not elaborate upon them here.

Note, when comparing these figures, the VER color scale covers a larger range in the three strong-SSW years ($0\text{-}7\times10^{-7}$ erg/cm^3-s) than it does in the others. Also, the layer-temperature colors cover a narrower range in the year 2008, to make the rapid variations in the mesosphere more apparent.

One also sees general similarities among the three strong-SSW years, 2004, 2006, and 2009, much as one does in the evolution of temperature structure revealed in Figures 1A and 1B for those years. Most notable are the extensive periods during which the OH layer was near or below 80 km at the northernmost latitudes, and of course the correlative increase in VER and layer temperature. However, for 2006 and 2009—when the SSWs occurred during the SABER observation period—one first sees a rise in the OH layer (~20 January both years, right at the time of the SSWs) and then a decline over a period of a ~7-10 days. In accord with previous discussion, one difference is the much larger range of latitudes over which these changes occurred in 2009 compared to 2006. The same is true of associated changes in VER and temperature.

In Figure 4B, one sees that the four stratospheric warming periods in 2008 also appear to have produced changes in OH layer altitude and VER. At the highest latitudes the layer altitude rose and fell by ~3-4 km, with no fewer than five maxima over the ~60 day course of the yaw cycle. At the same time, VER varied by a factor of three, in an inverse manner. In order to display temporal variations throughout the yaw cycle more clearly, Figure 5 plots slices from Figures 1A(b) and 4B. In Figure 5(a) one sees that upper- and middle-stratospheric temperatures (red, green) were characterized by quasi-periodic excursions of ~30-40 K. The first four maxima in those curves should closely match the nominal dates of the SSWs [42], which are indicated by vertical arrows. Indeed they do—except for the second one, for which, as noted earlier, the assigned date indicated by the dashed arrow appears to be about five days early. Meanwhile, mesospheric temperature (80 km, blue) is in antiphase, with little discernible lag. Moreover the OH layer altitude in the same latitude range, Figure 5(b), has the same quasi-periodicity, but with low layer altitudes appearing a few days after the SSW dates in all cases (provided the timing of the second warming is adjusted). So, for these events, mesospheric cooling appears to have come at the same time as middle-stratospheric warming, while the OH layer reached minimum levels immediately thereafter, followed by a rapid ascent of several km. See the further discussion in Section 3.4.

In 2007, Figure 4C, the OH layer does not seem to be sensitive to anything that occurred in the stratosphere. Given that a major SSW (day 55?) did take place during the SABER observations [41], and that other SSWs, including minor ones in 2008, had easily-observable effects, the lack of an obvious response here is a little surprising. If one looks closely near day 55, one finds a very modest lowering and brightening of the layer thereafter, consistent with what was seen in 2008. However, the increase in layer altitude at the highest latitudes near day 40, which is coincident—if not associated—with a blob of stratospheric warming seen in Figure 1A(c) at that time, seems to represent a larger perturbation. This suggests, although certainly does not prove, that warming events produce a continuum of effects in the mesosphere, whether or not they cross the threshold to qualify as SSWs.

As in 2007, the OH layer in 2005 appears to have been largely unaffected by variability at lower altitudes. In that year, as noted above, the stratosphere was quiescent, certainly compared to other SABER years if not historically [43]. Figure 4E shows two periods during which the OH layer rose modestly and dimmed, but no external forcing is apparent here or in Figure 1B(e).

In Figure 4G, variations of layer altitude and brightness appear shortly after the major SSW of 16 January, 2003. The SABER yaw occurred on that day, and by the time data were available the OH layer was already in descent and becoming brighter. The timing in this case is similar to that of the multiple events of 2008, the layer altitude reaching its minimum a few days after the SSW. But there is no sign of a rapid rise or brightening immediately thereafter, nor are the excursions as large as in 2008. There is a modest maximum in layer altitude on day 48, shortly before the minor SSW that occurred on 19 February (Table 1). This figure shows nothing that can be associated with the minor warming of 5-6 March.

In 2002, Figure 4H, the major warming of 17 February appears to have been preceded by a slight rise in the OH layer and followed by a descent and brightening of the layer. But the excursion in altitude was only slightly more than 2 km, so it is difficult to make much of it. In this case, the warming in the stratosphere, Figure 1B(h), occurred more gradually than in other years.

In any of these years, it is possible that notable effects occurred in localized regions without being apparent in the zonal mean. In 2004 and 2006, when the vortex was offset from the pole [44,46] we did find major longitudinal differences in the mesospheric temperature and OH layer superposed on the mean properties documented in Figures 1 and 4 [22]. In 2009, even though the stratospheric vortex was split [10,35], resulting in very large longitudinal variations at lower altitudes, the very strong mesospheric disruption occurred nearly uniformly about the pole. We have not searched systematically for zonal asymmetry in years with weaker disruptions of the mesosphere.

3.4 Comparison of Mesospheric Responses

We have made an interannual comparison of the timing of mesospheric responses to SSWs relative to their onset dates. We considered the three years with strong SSWs as one group, and other years with lesser disruptions--2002, 2003, 2007, and 2008—as another. In so doing, we assumed that the SSW of 2007 occurred on day 55, or 24 February, and we adjusted the date of the second minor warming of 2008 to day 38, or 7 February, from day 33 as given in Table 1 because temperature data, e.g. Figures 1A(b) and 5(a), suggest an error in the assigned date [42]. Also, the appearance of the four rapidly-repeating warmings that year makes it difficult to isolate effects of any single one of them, so the 2008 data are plotted separately.

Figures 6(a) and 6(b) show daily zonal-mean temperature at 70 and 80 km, respectively, in the high-latitude bin 78-84ºN for the years with strong SSWs. Figures 7(a) and 7(b) show the same thing for the years other than 2008 that had lesser SSWs. In Figure 6, the mesospheric temperature response is clearly very similar in all these years, at both altitudes. In 2006 and 2009, modest warming took place just prior to the events, cooling occurred during and after them, and the temperature then rose once again as the stratopause reformed at ~80 km. At 70 km the peak cooling came ~5 days after the SSW in 2006 and ~10 days after the one in 2009, with a temperature drop that approached 50 K in the latter year. At 80 km and above, however, it was nearly coincident with the event. Variations that occurred after the SABER observations began in 2004 are quite like those of the other two years, so it is fair to speculate that the response at the time of that SSW would also have looked similar if it could have been viewed by the instrument.

In the years with less-intense SSWs, Figure 7 shows that cooling occurred each year at 70 km just after the SSWs occurred. However, there was no detectable prior warming as in the "strong" years. And, also unlike those years, there was no obvious cooling at 80 km and above, with the possible exception of 2003. However, Figure 8 shows data at three altitudes in 2008, and in that year cooling did occur throughout the mesosphere, as high as 90 km, near the date of all four SSWs.

Moreover, in 2008 the timing of the cooling was altitude-dependent. (This can also be seen in Figure 1A(b), where the mesospheric cooling regions appear to be descending with time during each of the first four events in 2008, much as the stratospheric warming regions do.) Figure 8 shows that the greatest cooling at 90 km occurred ~3-5 days prior to the dates of the SSWs, and it came successively later at the lower altitudes shown. At 70 km it occurred just at, or very slightly after, the times of all the SSWs, which is exactly what Figure 7(a) shows for the other years.

For the year 2003, it is not possible to determine whether a temperature minimum occurred at 80 km around the time of the SSW because the onset was right at the beginning of the SABER yaw cycle. Figure 7(b) does show a rise in temperature immediately thereafter, so there may have been one. Much clearer is the cooling at both 70 and 80 km near the time of the "nearly major" [44] warming of 19 February. In that case, the temperature minimum at 70 km occurred on 20 February, about 35 days after the major stratwarm, but at 80 km it was on 18 February. One sees that the timing of this cooling episode is exactly like what took place repeatedly at the different altitudes in 2008. Note, no sign of the "nearly major" warming of ~5-6 March 2003 can be discerned.

Figure 9(a) shows the OH layer altitude, in the same format, for the years with intense SSWs. Figure 9(b) does so for those with moderate ones. Also, Figure 5(b) shows the variation for year 2008, with the timing of the four SSWs indicated by arrows. The most notable feature in any of these plots is the abrupt rise in the layer height that occurred at the time of the intense SSWs in 2006 and 2009, and the plunge to record-low values in the weeks following. The latter has been documented for 2004 and 2006 [22] but the initial rise is also remarkable. It is difficult to tell whether any increase in altitude is seen in the other years, Figure 9(b). What one does see there is a very modest and brief descent of the OH layer, in all three years, within a few days of the SSW. The significance of such relatively minor perturbations on the mean layer height would be easy to overlook if they were not so consistent, and indeed consistent with what was seen in Figure 5(b) for 2008. In that year, higher OH layers preceded each SSW but lower ones followed them. The extent of the rise and fall was only ~2 km, far less than the changes in the "strong SSW" years but comparable to those shown in Figure 9(b). However, the correlation with onset dates—minimum altitudes occurring a few days after—is so clear that it is difficult to ascribe it to coincidence. It follows that the drop in altitude in the three years shown Figure 9(b) is probably not measurement noise, or coincidence, either.

After considering the mesospheric effects of all these SSWs, the fact that the literature (as reviewed in Section 2) reflects ambiguities about their timing and altitudinal extent is not surprising. The determination [20] that SSWs produce an anticorrelation of temperatures between 10 and 0.1 hPa (~65 km) but not necessarily between 10 and 0.01 hPa (~80 km) agrees with our results, which show that cooling occurs consistently at 70 km, its peak nearly coincident with the SSW date, while it may or may not be found to be significant higher up. The ancillary conclusion that OH rotational temperatures may not reflect the cooling is thus borne out.

Our results also show that when cooling does extend higher into the mesosphere during "moderate" years, it precedes the SSW by a few days there (consistently so in 2008; a hint of the same in 2003). This is in accord with some OH results [17,18]—which however indicate a greater time discrepancy than the ~3-5 days we see at 90 km—and not others [16,21]. We note that for the two "strong" SSWs directly observed by SABER, however, cooling in the upper mesosphere occurred right about the onset times. In those years, it did precede the cooling at 70 km, which occurred somewhat later relative to the events than in less-disturbed years.

3.5 Equatorial Temperature

Because of considerations raised in Section 2, we decided to look at SABER data in the equatorial region during the NH winters discussed above. The purpose was to see if some sort of systematic response of low-latitude temperature to the presence of polar disturbances, particularly the strongest ones, could be identified in the data.

Any study of the low-latitude middle atmosphere using data from limb-looking satellites in high-inclination orbits is complicated by the presence of strong atmospheric tides. On any given day in any particular latitude band, data acquisition takes place at just two local times (LTs), meaning that reliable daily means of temperature—or of any field modulated by the tides—cannot be extracted from single-day measurements. The observation times do change slowly as the satellite orbit precesses, enabling a nearly-complete sampling of LT over each yaw cycle, so long-term means can eventually be extracted that way. But this inevitably obscures variations occurring on time scales of several days.

[Similar considerations apply to higher latitudes as well. But tidal amplitudes are generally much smaller there, and we have ignored their effects in the work described in previous sections.]

In the case of SABER, the LT difference between ascending and descending nodes is about nine hours at the equator. The yaw cycles repeat for nearly the same periods each year, so LTs of the observations are almost the same for a given day each year. On the ascending side, measurements start in late morning at the beginning of the cycle and progress backwards all the way through midnight to ~22 hours at the end. On the descending side, they start in very early morning and progress backwards to about 13 hours. Thus, local midnight is viewed at the beginning and the end of the yaw cycle. Local noon is not observed at all.

The figures discussed below include plots showing these measurement times. Some of them give "zonal mean" temperature in the latitude range 6ºS-6ºN for several yaw cycles, with measurements on one side of the orbit discriminated from those on the other. By this, we simply mean that all data on the ascending side in this latitude bin are averaged over a day without regard to longitude, and descending data similarly. The available results are not true global daily means, but rather global means for the LT bins sampled on any given day. Natural day-to-day atmospheric variability is therefore conflated with effects of the slowly-varying LT, as are longer-term (seasonal) effects. One seasonal effect that is relevant here is the varying strength of the migrating diurnal tide, which maximizes near vernal equinox.

Figure 10 shows temperature results for 2009. One sees that the equatorial stratosphere was close to uniform throughout the ~60 days of observations. (Compared to the polar region, it was strikingly uniform.) Small differences can be seen when the ascending and descending data are compared, however. In the ascending data the stratopause was close to 50 km throughout, whereas in the descending data its altitude fell by about 6 km in the latter part of the yaw cycle. The stratopause lowering is replicated in plots using pressure instead of altitude (not shown) and in several other years as well. In the ascending data, the stratopause temperature was between 262 and 266 K through the end of January, e.g. during and immediately after the SSW. It fell slowly throughout this period, but then underwent an abrupt increase (~12 K) in the first two weeks of February. In the descending data the temperature was ~3-4 K higher in January, and it warmed quite slowly from ~day 20 through early February. In both cases, the warmest it got was ~273 K. The LTs that were observed during and following the SSW were mid morning on one side and late evening on the other.

The mesosphere was, not surprisingly, much more variable. The most obvious variable features are temperature inversion layers (TILs) that reached their peaks in the middle of February (descending data) and late February (ascending data). In both cases, TIL amplitudes exceeded 60 K at some point. We should note, although it is not completely obvious in Figure 10, that smaller TILs were actually present in the mesosphere throughout the yaw cycle, on both sides.

Figure 11 gives information in the same format for year 2006, the other year with an intense SSW at the beginning of SABER observations of northern winter. Similarities in the two years are obvious, differences are subtle. The lowering of the stratopause in the ascending data was very small in 2009, but more apparent in 2006; descending data are similar in the two years. Stratopause temperatures were a little cooler overall in 2006, and excursions were somewhat less. In fact, the equatorial stratopause exhibited greater fluctuations in temperature in 2009 than in any other SABER year. The mesosphere in 2006 produced TILs that were very similar to those of 2009 (and every other SABER year except 2005, when they were much diminished).

As noted earlier, changes in the tropical middle atmosphere at certain locations have been attributed to the remote influence of SSWs—in particular, warming in the upper stratosphere and cooling in the mesosphere [23,24,25]. While modest in comparison to the disruption of the polar region, one might expect to see such signs in the SABER data, especially in years with the most intense SSWs. In fact, there is no discernable sign of cooling in the lower mesosphere in middle/late January 2009, Figure 10. But in 2006, a year with an intense SSW at exactly the same time, a distinct cooling trend can be seen in January and early February, in Figure 11. The contrasts are made clearer in plots with slices taken at specific altitudes, of which Figure 12 is an example using an altitude of 70 km.

The mesospheric cooling trend in 2006 is similar to what was seen in nightly-mean lidar results from Gadanki that year [24]. Considering the different approaches to sampling the atmosphere, and the different location(s), this agreement is at least encouraging. As to the question of whether or not to attribute this to the SSW, however, the absence of coincident cooling in 2009 suggests that the appearance of a strong SSW is at best an insufficient condition. More to the point, in several other years—notably, 2005 and 2007—cooling trends also appeared in the lower mesosphere between mid January and early February, mimicking quite closely what was seen in 2006. But no SSWs occurred during that period in either year. In 2008, the year with four SSWs, there was a modest <u>warming</u> at 70 km at the time of the first one (25 January). This was followed by a slow, uninterrupted decrease in temperature extending into middle February. We therefore can say we have not found a consistent correlation, in the SABER data, between SSWs and equatorial mesospheric cooling.

It is worth noting that the difficulty of trying to extract signatures of remote short-duration events from data in this form is formidable, given that competing LT and seasonal variations have not been removed. Above and beyond that, zonal means necessarily obscure fluctuations that may not be zonally symmetric—which, considering that SSWs usually are not, one might expect to find even at remote sites. There is also the consideration that our analysis was centered exactly at the equator, while all the other observations cited above were at slightly higher latitudes. The failure of SABER to confirm previous observations in the tropical middle atmosphere may therefore not be conclusive.

At the tropical stratopause, tidal effects are much smaller than at higher altitudes, but certainly not negligible. We find that the temperature in our data varied by ~6-7 K. What part of that variation is a daily occurrence, as opposed to a seasonal change, is difficult to say. However, the correlation of SSWs with equatorial upper-stratosphere warming has also been the subject of past analyses—again, at locations somewhat offset from ours—so we looked at stratopause temperature (and altitude) in each of the SABER years, trying to discover a correlation. In both 2006 and 2009, we found that the stratopause was cooling very slightly at the beginning of the yaw cycle. In 2006, it began to warm once again right at the time of the SSW, although at different rates in the morning (ascending data) and late night hours (descending). In 2009, the stratopause also warmed eventually. It started doing so a day or two after the SSW in the descending data, but continued to cool for almost ten days in the ascending data before a sudden increase occurred.

Plots in Figure 13 show this (and more), in a somewhat complicated way. They give the daily mean ascending and descending stratopause altitudes and temperatures in both years, plotted as a function of local time in such a way (by adding 24 hrs to prenoon data) that observations near local midnight are shown together in the middle of the figures. The purpose of plotting data against LT was to try to uncover the systematic tidal effects. The important thing to note here is that, in accord with the earlier discussion, results from the beginning of the yaw cycle are at the later local times—e.g., at the right on each plot—and those from the end are earlier, or on the left. One thus sees that at the beginning of the yaw cycle in 2009 just before the SSW, the temperature was dropping in both ascending (red triangles, LT>30 hrs) and descending (blue, LT~24 hrs) data, prior to a subsequent warming trend in each case. The same was true of the ascending data in 2006.

Sridharan et al [24] report a "sudden increase" in the stratopause temperature over Gadanki on 21 January 2006, with an overall change of 5-10 K during a period of 20 days. Considering that their measurements were taken at night, they are more nearly comparable to our descending data, which show a very slow rise of ~2 K (comparable to measurement noise) at the corresponding time. Variability at a single site would be expected, of course, to be considerably greater than that found in a zonal mean.

Looking at the stratopause temperature in other years, we found no association of conspicuous warming trends with SSW dates.

We constructed plots like those in Figure 13 for the other SABER years, hoping to find variations with LT that were consistent from year to year, in order to propose a "baseline" against which short-term changes could be measured. There were some similarities, but they were not sufficiently strong to enable the isolation or removal of tidal effects. Among other things, we found that a change in altitude of the stratopause in the evening/afternoon hours (descending data; ~6 km in 2009) occurs every year, but is twice as large in some years as it is in others. We also found that in some years, the stratopause altitude near midnight is the same in January (descending data) as in March (ascending), but in other years discrepancies like those in Figure 13(b) suggest that seasonal changes are quite important. The same was true with temperature near midnight, and the years in which the altitudes were the same were not necessarily those in which the temperatures were. We were also unable to correlate SSW years with any of these patterns.

Finally, in all the even-numbered SABER years, the QBO was in its eastward phase at the time of NH winter, the opposite being true in odd-numbered years. We found no correlation of the QBO with perturbations of any quantity we investigated.

4. SUMMARY

One purpose for this report was to document, for the first time, the disruption of the mesosphere that occurred in the aftermath of the very intense SSW of January 2009—and to compare it with what had already been reported for 2004 and 2006 [22]. As it happens, conditions were so similar to what was described previously that it became equally useful to compare and contrast conditions with other SABER years, taking advantage of the fact that SSWs were seen in seven of those eight NH winters. We also looked at precursor periods wherever possible.

The foregoing descriptions can be viewed as supplements to the normal stratospheric/ meteorological investigations of SSWs in the polar regions. Nothing we have seen is clearly at variance with extensive descriptions of these winters that have already been given [35,36,42,44,46]. However, we did find it necessary to adjust the date of the second minor warming of 2008.

With regard to 2009, we found that right at the time of the SSW on 21 January, the OH layer rose considerably and its emissions were much weaker than normal. Subsequently, the layer plunged to altitudes below 80 km and became a lot brighter, much as in 2004 and 2006. The temperature structure at normal mesospheric altitudes was completely altered, also as in those years. The principal difference was that in 2009 the mesospheric disruptions extended much farther south. There were also some differences in timing, the rates at which the stratopause reformed at high altitudes and then returned to normal, and the fact that the mesosphere in 2009 was much more nearly zonally symmetric for most of the winter than in similar years. The latter point is interesting, because the SSW was a split-vortex event and the stratosphere was distinctly not uniform about the pole.

Examination of the 2009 data reinforces our earlier suggestion [22] that changes in the easily-observed OH layer might serve as a proxy for disruptions of mesospheric temperature structure, and changes in polar winter meteorology in general.

We gave a general description of each of the SABER years, using zonal-mean temperature and OH layer data. The polar stratospheric and mesospheric temperature structure is quite variable in all years, including 2005 when there was no SSW. Some of the SSWs (including minor warmings) show up quite clearly in it and some do not. However, the years 2004, 2006, and 2009 are strikingly different from all the others.

Mesospheric cooling is associated with each SSW. The altitude range over which it can be detected is different from year to year, being limited to lower regions (~70 km) in several years (2002, 2007) but also appearing higher up in others.

The four SSWs that occurred in a space of about a month in 2008 produced very consistent effects in the mesosphere. We showed that peak cooling preceded the SSWs by ~3-5 days at 90 km and by ~2 days at 80 km, while that at 70 km was coincident with the SSW or slightly lagging. In other years with the less intense SSWs, cooling was timed similarly where it could be seen.

The prominent initial rise in the OH layer noted in 2009 also took place in 2006. In 2008 the OH layer altitude varied quasi-periodically. The timing was determined by the SSWs, with maximum altitudes occurring a few days before the SSWs in that year. In other years there was no apparent increase in the height prior to or at the time of the events. However, modest but significant decreases occurred a few days afterwards.

The inverse relationship between OH layer altitude and VER holds in all portions of all years, regardless of the intensity of any SSW or the extent of the associated mesospheric disruptions. The extremes of altitude and brightness of course occurred in the aftermath of the most intense SSWs.

By looking at SABER data near the equator, we investigated suggestions about warming in the tropical upper stratosphere, as well as cooling in the mesosphere. We found traces of both sorts of changes in 2006, one year for which they were reported [24]. However, there was no such behavior in other SSW years, including 2009 when it might have been expected. Also, cooling quite similar to that of 2006 occurred in years with no SSWs. As a result of this, we determined that the SABER data are not at all conclusive in regards to either the warming or the cooling. It has to be acknowledged that the combination of strong atmospheric tides and discrete sampling in LT make it difficult to extract such signatures, of modest short-term perturbations to the mean state, from SABER data.

One of the suggestions of this study is that SSWs produce a continuum of effects in the mesosphere. Even as there is a certain arbitrariness (generally acknowledged) about the definition of a major warming, it may be that associated perturbations of the stratosphere and mesosphere, similar to what is documented here, occur regularly, even at times when the threshold conditions are not close to being met. For example, cooling appears consistently with stratwarms, but our data contain other periods when the stratosphere apparently warmed and the mesosphere cooled. When it did cool, the range of altitudes over which that happened varied greatly, as did the extent of the temperature changes. The OH layer also seemed to be perturbed at the time of many SSWs, but not only then.

We intend to complete some follow-up work on the tropics. This will include an examination of temperature variations at latitudes somewhat north of the equator, to better correlate with other observations. Also, in view of the suggestions of long-range teleconnections through the meridional circulation, we will look at the OH layer to see if it can tell us anything.

We also intend to study the January-March period of 2010, which may provide an example of a relatively undisturbed northern winter.

REFERENCES

1. Russell, J.M. III, M.G. Mlynczak, L.L Gordley, J. Tansock, and R. Esplin, "An overview of the SABER experiment and preliminary calibration results," *Proc. SPIE*, **3756**, 277-288, 1999.

2. Scherhag, R., "Die explosionartigen stratosphärenerwärmungen des spätwinters 1952," *Ber. Det. Wetterdienstes* (US Zone), **38**, 51-63, 1952.

3. Andrews, D.G., J.R. Holton, and C.B. Leovy, **Middle Atmospheric Dynamics**, 1st edition, Academic Press, San Diego, 1987.

4. Labitzke, K., "Stratospheric-mesospheric midwinter disturbances: A summary of observed characteristics," *J. Geophys. Res.*, **86**, 9665-9678, 1981.

5. Charlton, A.J., and L.M. Polvani, "A new look at stratospheric sudden warmings: Part I: Climatology and modeling benchmarks," *J. Clim.*, **20**, 449-469, 2007.

6. Limpasuvan, V., D.W.J. Thompson, and D.L. Hartmann, "The life cycle of the northern hemisphere sudden stratospheric warmings," *J. Clim.*, **17**, 2584-2596, 2004.

7. Matsuno, T., "A dynamical model of the stratospheric sudden warming," *J. Atmos. Sci.*, **28**, 1479-1494, doi:10.1175/1520-0469(1971)028, 1971.

8. Martius, O., L.M. Polvani, and H.C. Davies, "Blocking precursors to stratospheric sudden warming events," *Geophys. Res. Lett.*, **36**, L14806, doi:10.1029/2009GL038776, 2009.

9. Woollings, T., A. Charlton-Perez, S. Ineson, A.G. Marshall, and G. Masato, "Associations between stratospheric variability and tropospheric blocking," *J. Geophys. Res.*, **115**, D06108, doi:10.1029/2009JD012742, 2010.

10. NASA, 2009: http://earthobservatory.nasa.gov/IOTD/view.php?id=36972.

11. Liu, H.-L. and R.G. Roble, "A study of a self-generated stratospheric sudden warming and its mesospheric-lower thermospheric impacts using the coupled TIME-GCM/ CCM3," *J. Geophys. Res.*, **107** (D23), 4695, doi:10.1029/2001JD001522, 2002.

12. Holton, J.R., "The influence of gravity wave breaking on the general circulation of the middle atmosphere," *J. Atmos. Sci.*, **40**, 2497-2507, 1983.

13. Labitzke, K., "Temperature changes in the mesosphere and stratosphere connected with circulation changes in winter," *J. Atmos. Sci.*, **29**, 756-766, 1972a.

14. Labitzke, K., "The interaction between stratosphere and mesosphere in winter," *J. Atmos. Sci.*, **29**, 1395-1399, 1972b.

15. Whiteway, J.A., and A.I. Carswell, "Rayleigh lidar observations of thermal structure and gravity wave activity in the high Arctic during a stratospheric warming," *J. Atmos Sci.*, **51**, 3122-3136, 1994.

16. Myrabø, H.K., C.S. Deehr, and B. Lybekk, "Polar cap OH airglow rotational temperatures at the mesopause during a stratospheric warming event," *Planet. Spa. Sci.*, **32**, 853-856, doi:10.1016/ 0032-0633(84)90009-6, 1984.

17. Walterscheid, R.L., G.G. Sivjee, and R.G. Roble, "Mesospheric and lower thermospheric manifestations of a stratospheric warming event over Eureka, Canada (80ºN)," *Geophys. Res. Lett.*, **27**, 2897-2900, 2000.

18. Sigernes, F., N, Shumilov, C.S. Deehr, K.P. Neilson, T. Svenøe, and O. Havnes, "Hydroxyl rotational temperature record from the auroral station in Adventdalen, Svalbard (78ºN, 15ºE)," *J. Geophys. Res.*, **108** (A9), 1342, doi:10.1029/2001JA009023, 2003.

19. Thayer, J.P., and J.M. Livingston, "Observations of wintertime arctic mesosphere cooling associated with stratospheric baroclinic zones," *Geophys. Res. Lett.*, **35**, L18803, doi:10. 1029/2008GL034955, 2008.

20. Siskind, D.E., L. Coy, and P. Espy, "Observations of stratospheric warmings and mesospheric coolings by the TIMED SABER instrument," *Geophys. Res. Lett.*, **32**, L09804, doi:10.1029/ 2005GL022399, 2005.

21. Cho, Y.-M., G.G. Shepherd, Y.-I. Won, S. Sargoytchev, S. Brown, and B. Solheim, "MLT cooling during stratospheric warming events," *Geophys. Res. Lett.*, **31**, L10104, doi:10.1029/ 2004GL019552, 2004.

22. Winick, J.R., P.P. Wintersteiner, R.H.Picard, D. Esplin, M.G. Mlynczak, J.M. Russell III, and L.L.Gordley, "OH layer characteristics during unusual boreal winters of 2004 and 2006," *J. Geophys. Res.*, **114**, A02303, doi:10.1029/2008JA013688, 2009.

23. Sivakumar, V., B. Morel, H. Bencherif, J.L. Baray, S. Baldy, A. Hauchecorne, and P.B. Rao, "Rayleigh lidar observation of a warm stratopause over a tropical site, Gadanki (13.5ºN, 79.2ºE)," *Atmos. Chem. Phys.*, **4**, 1989-1996, 2004.

24. Sridharan, S., S. Sathishkumar, and K. Raghunath, "Rayleigh lidar observations of enhanced stratopause temperature over Gadanki (13.5ºN, 79.2 ºE) during major stratospheric warming in 2006," *Ann. Geophys.*, **27**, 373-379, 2009.

25. Shepherd, M.G., D.L. Wu, I.N. Fedulina, S. Gurubaran, J.M. Russell, M.G. Mlynzcak, and G.G. Shepherd, "Stratospheric warming effects on the tropical mesospheric temperature field," *J.A.S.T.P.,* **69**, 2309-2337, doi:10.1016.j.jastp.2007.04.009, 2007.

26. Kodera, K., "Influence of stratospheric sudden warming on the equatorial troposphere," *Geophys. Res. Lett.*, **33**, L06804, doi:10.1029/2005GL024510, 2006.

27. Karlsson, B., H. Körnich, and J. Gumbel, "Evidence for interhemispheric stratosphere-mesosphere coupling derived from noctilucent cloud properties," *Geophys. Res. Lett.*, **34**, L16806, doi:10.1029/2007GL030282, 2007.

28. Karlsson, B., C. McLandress, and T.G. Shepherd, "Interhemispheric mesospheric coupling in a comprehensive middle atmosphere model," *J.A.S.T.P.*, **71**, 518-530, doi:10.1016/ j.jastp.2008.08. 006, 2009.

29. Dyrland, M.E., F.J. Mulligan, C.M. Hall, F. Sigernes, M. Tsutsumi, and C.S. Deehr, "Response of OH airglow temperatures to neutral air dynamics at 78ºN, 16ºE during the anomalous 2003-2004 winter," *J. Geophys Res.*, **115**, D07103, doi:10.1029/2009JD 012726, 2010.

30. Wintersteiner, P., "Anomalous conditions in the middle atmosphere during boreal winters of 2004 and 2006," Air Force Laboratory Technical Report, AFRL-RV-HA-TR-2008-1006, 2007.

31. Mlynczak, M. and S. Solomon, "A detailed evaluation of the heating efficiency in the middle atmosphere," *J. Geophys. Res.*, **98**, 10517-10541, 1993.

32. Mlynczak, M., "A new perspective on the molecular oxygen and hydroxyl airglow emissions," *J. Geophys. Res.*, **104**, 27535-27543, 1999.

33. Labitzke, K., and H. van Loon, "Associations between the 11-year solar cycle, the QBO, and the atmosphere. Part I: The troposphere and stratosphere in northern hemisphere winter," *J.A.T.P.*, **50**, 197-206, 1988.

34. Camp, C.D., and K.-K. Tung, "The influence of the solar cycle and QBO on the late-winter stratospheric polar vortex," *J. Atmos. Sci.*, **64**, 1267-1283, doi:10.1175/JAS3883.1, 2007.

35. Manney, G.L., M.J. Schwartz, K. Krüger, M.L. Santee, S. Pawson, J.N. Lee, W.H. Daffer, R.A. Fuller, and N.J. Livesey, "Aura Microwave Limb Sounder observations of dynamics and transport during the record-breaking 2009 Arctic stratospheric major warming," *Geophys. Res. Lett.*, **36**, L12815, doi:10.1029/2009GL038586, 2009.

36. Labitzke, K., and M. Kunze, "On the remarkable Arctic winter in 2008/2009," *J. Geophys. Res.*, **114**, D00I02, doi:10.1029/2009JD012273, 2009.

37. Wintersteiner, P., and E. Cohen, "Observations and modeling of the upper mesosphere: Mesopause properties, inversion layers, and bores," Air Force Laboratory Technical Report, AFRL-VS-HA-TR-2005-1162, 2005.

38. Mertens, C.J., F.J. Schmidlin, R.A. Goldberg, E.E. Remsberg, W.D. Pesnell, J.M. Russell III, M.G. Mlynczak, M. López-Puertas, P.P. Wintersteiner, R.H. Picard, J.R. Winick, and L.L. Gordley, "SABER observations of mesospheric temperatures and comparisons with falling sphere measurements taken during the 2002 summer MaCWAVE campaign," *Geophys. Res. Lett.*, **31**, L03105, doi:10.1029/2003GL018605, 2004.

39. Mlynczak, M., F.-J. Martin-Torres, G. Crowley, D.P. Kratz, B. Funke, G. Lu, M. López-Puertas, J.M. Russell III, J. Kozyra, C. Mertens, R. Sharma, L. Gordley, R. Picard, J. Winick, and L. Paxton, "Energy transport in the thermosphere during the solar storms of April 2002," *J. Geophys. Res.*, **110**, A12S25, doi:10.1029/2005JA011141, 2005.

40. Remsberg, E.E., B.T. Marshall, M. Garcia-Comas, D. Kreuger, G.S. Lingenfelser, J. Martin-Torres, M.G. Mlynczak, J.M. Russell III, A.K. Smith, Y. Zhao, C. Brown, L.L. Gordley, M.J. López-Gonzalez, M. López-Puertas, C.-Y. She, M.J. Taylor, and R.E. Thompson, "Assessment of the quality of the version 1.07 temperature versus pressure profiles of the middle atmosphere from TIMED/SABER," *J. Geophys. Res.*, **113**, D17101, doi:10.1029/2008JD010013, 2008.

41. Institute of Meteorology, "30 hPa monthly mean North Pole temperatures," Freie Universität Berlin, URL: http://www.geo.fu-berlin.de/met/ag/strat/produkte/northpole/index.html, last modified July 21, 2009.

42. Wang, L., and M.J. Alexander, "Gravity wave activity during stratospheric sudden warmings in the 2007-2008 Northern Hemisphere winter," *J. Geophys. Res.*, **114**, D18108, doi: 10.1029/2009JD011867, 2009.

43. Manney, G.L., M.L. Santee, L. Froidvaux, K. Hoppel, N.J. Livesey, and J.W. Waters, "EOS MLS observations of ozone loss in the 2004-2005 Arctic winter," *Geophys Res. Lett.*, **33**, L04802, doi:10.1029/2005GL024494, 2006.

44. Manney, G.L., K. Krüger, J.L. Sabutis, S.A. Sena, and S. Pawson, "The remarkable 2003-2004 winter and other recent warm winters in the Arctic stratosphere since the late 1990s," *J. Geophys. Res.*, **110**, D04107, doi:10.1029/2004JD005367, 2005.

45. Shepherd, G.G., Y.-M. Cho, and G. Liu, "Correlations of mesospheric variability and their relation to the large-scale circulation during polar winter," *J.A.S.T.P.*, **69**, 2279-2291, 2007.

46. Manney, G.L., K. Krüger, S. Pawson, K. Minschwaner, M.J. Schwartz, W.H. Daffer, N.J. Livesay, M.G. Mlynczak, E.E. Remsberg, J.M. Russell III, and J.W. Waters, "The evolution of the stratopause during the 2006 major warming: Satellite data and assimilated meteorological analyses," *J. Geophys. Res.*, **113**, D11115, doi:10.1029/2007JD009097, 2008.

APPENDIX

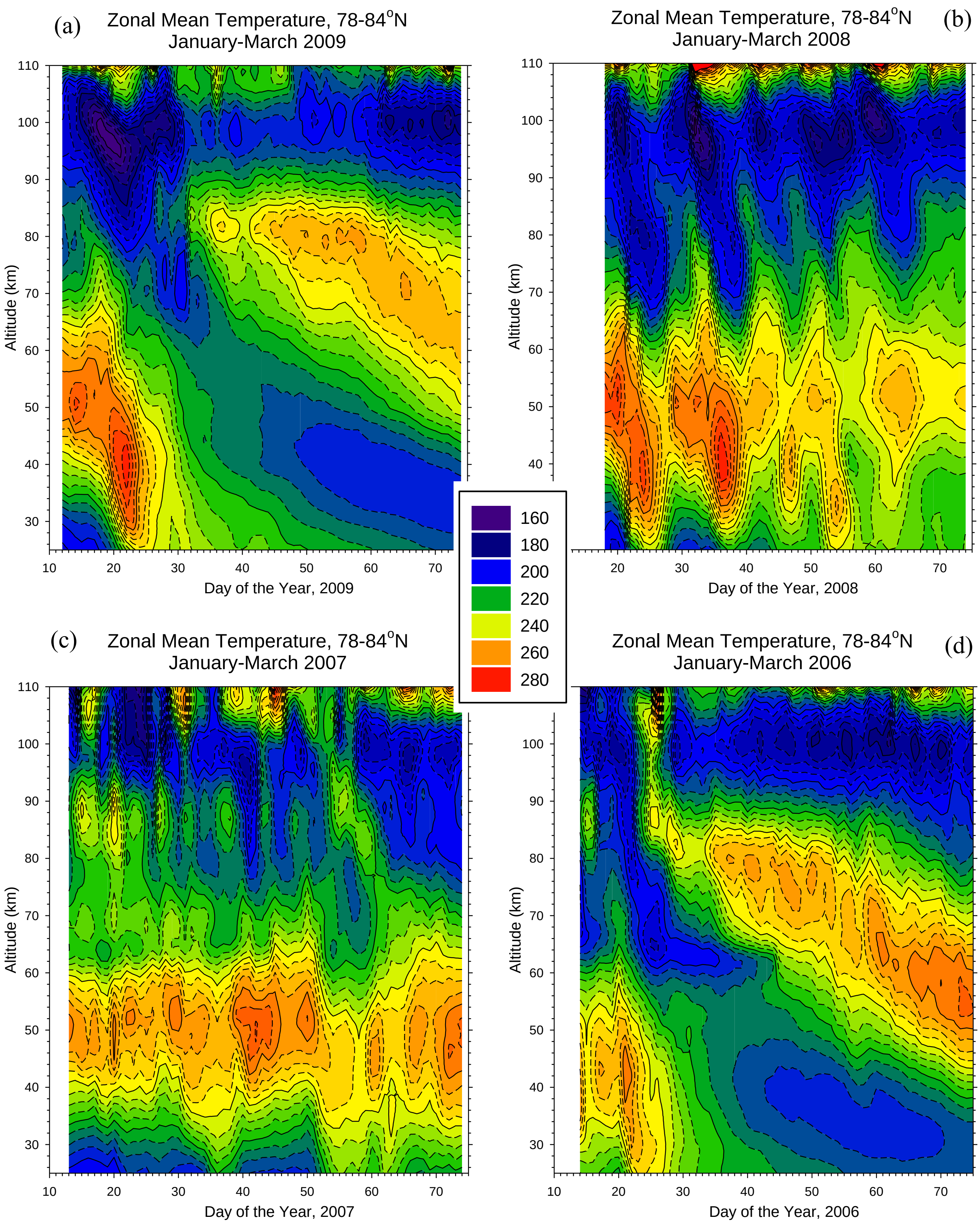

Figure 1A. SABER Daily Zonal Mean Temperature in the Latitude Band 78º-84ºN, 2006-2009

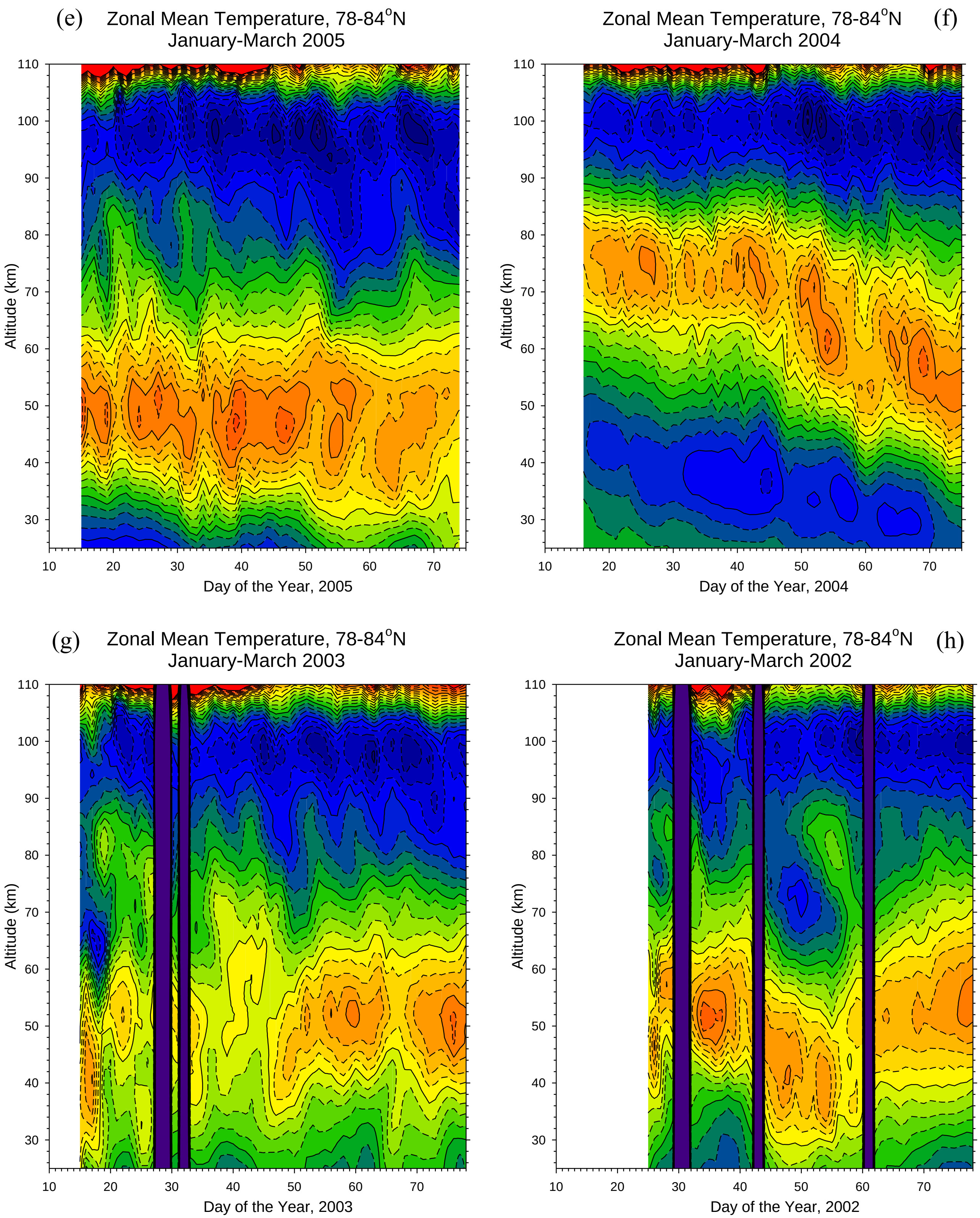

Figure 1B. SABER Daily Zonal Mean Temperature in the Latitude Band 78°-84°N, 2002-2005
Same Temperature Scale as Figure 1A

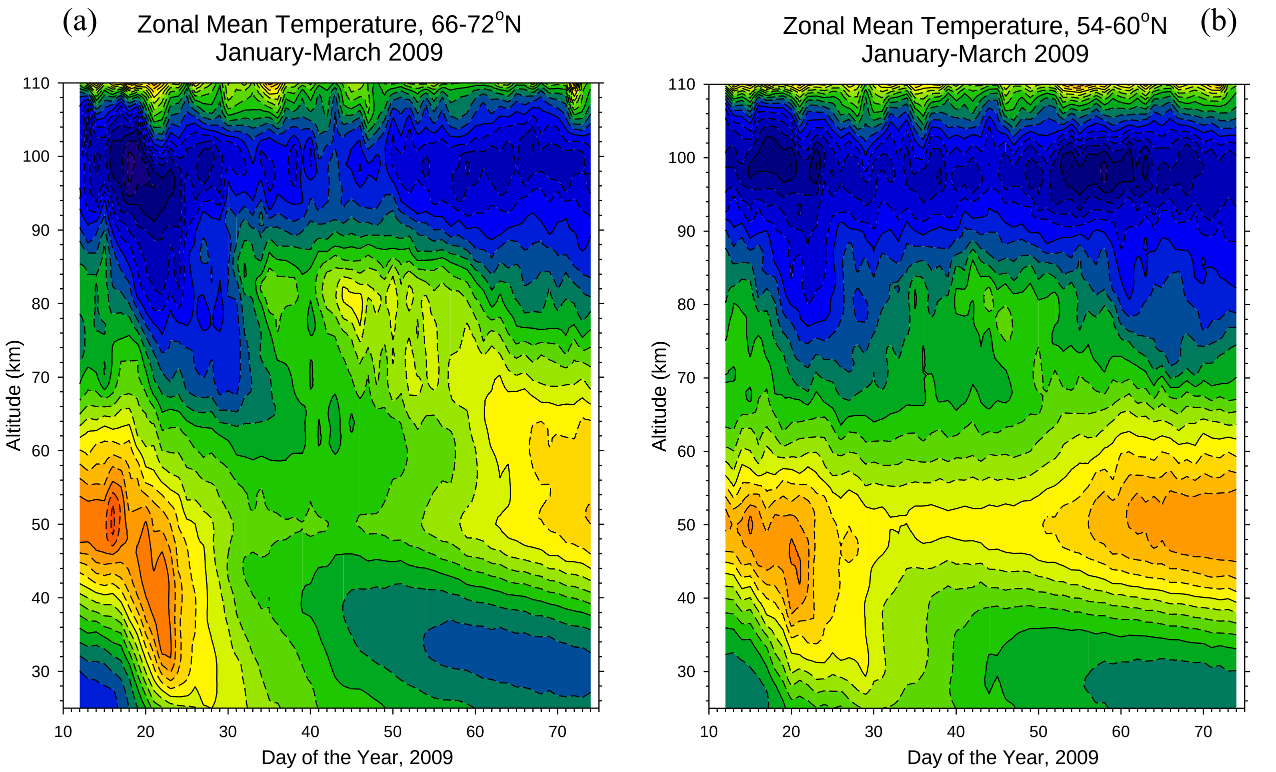

Figure 2. SABER Daily Zonal Mean Temperature for (a) 66-72ºN and (b) 54-60ºN, 2009 Same Scale as Figure 1A

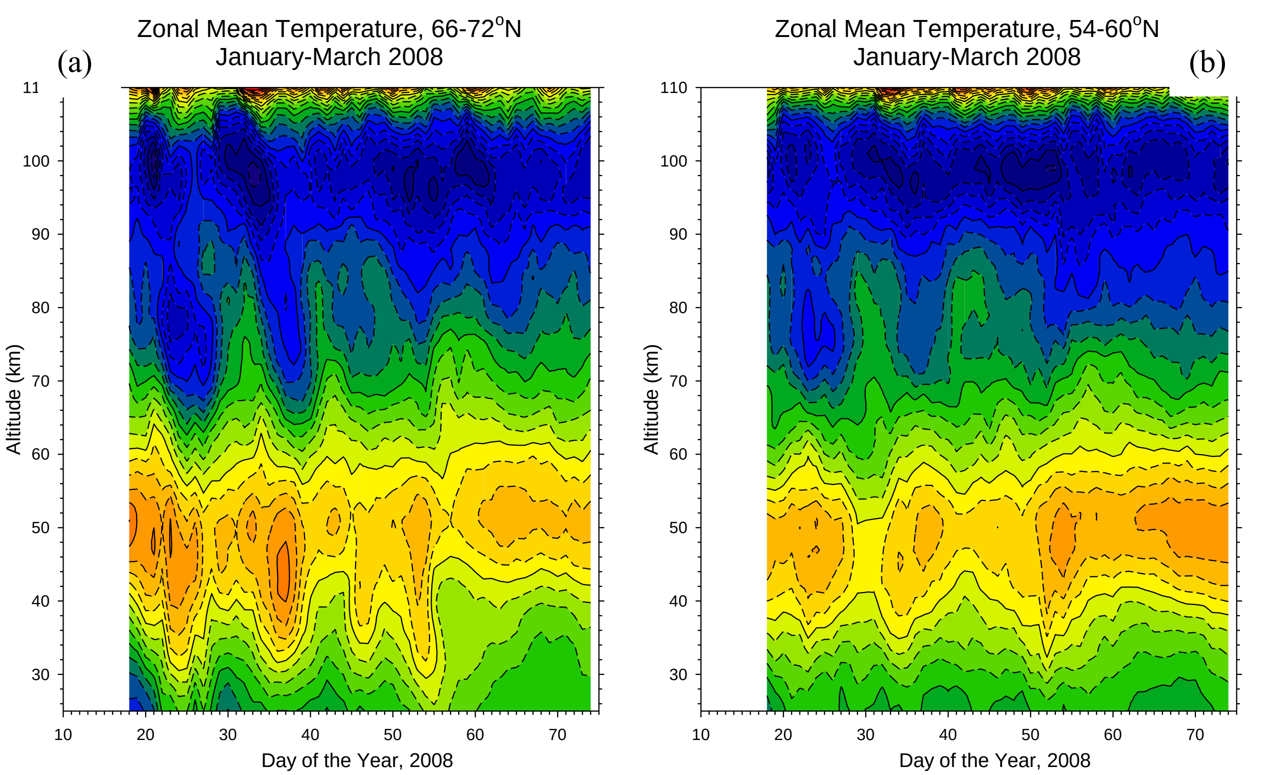

Figure 3. SABER Daily Zonal Mean Temperature for (a) 66-72ºN and (b) 54-60ºN, 2008 Same Scale as Figure 1A

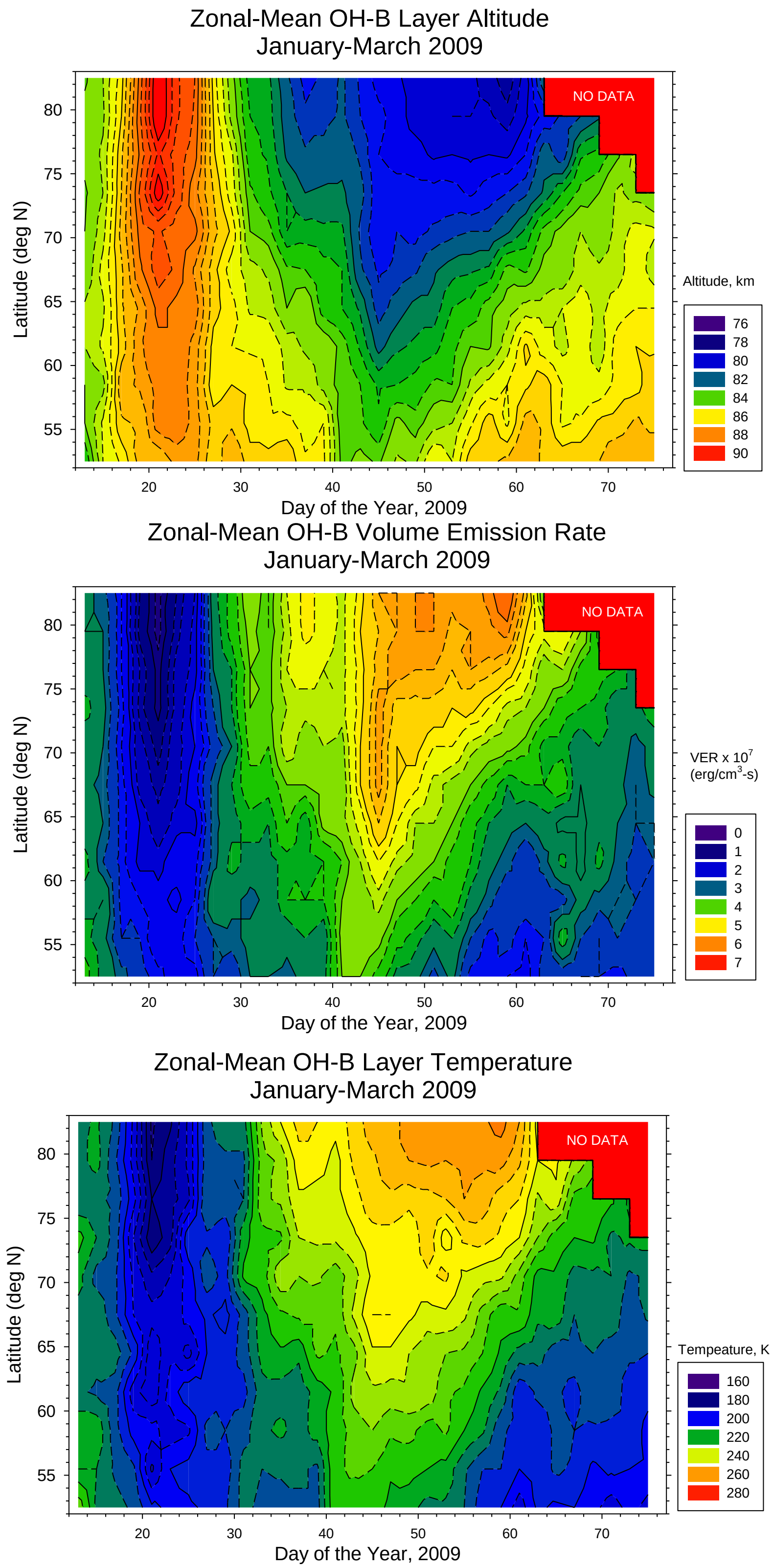

Figure 4A. OH Layer Properties in 2009: (Top) Layer Altitude, km; (Middle) VER, erg/cm^3-s Times 10^7; (Bottom) Temperature, K

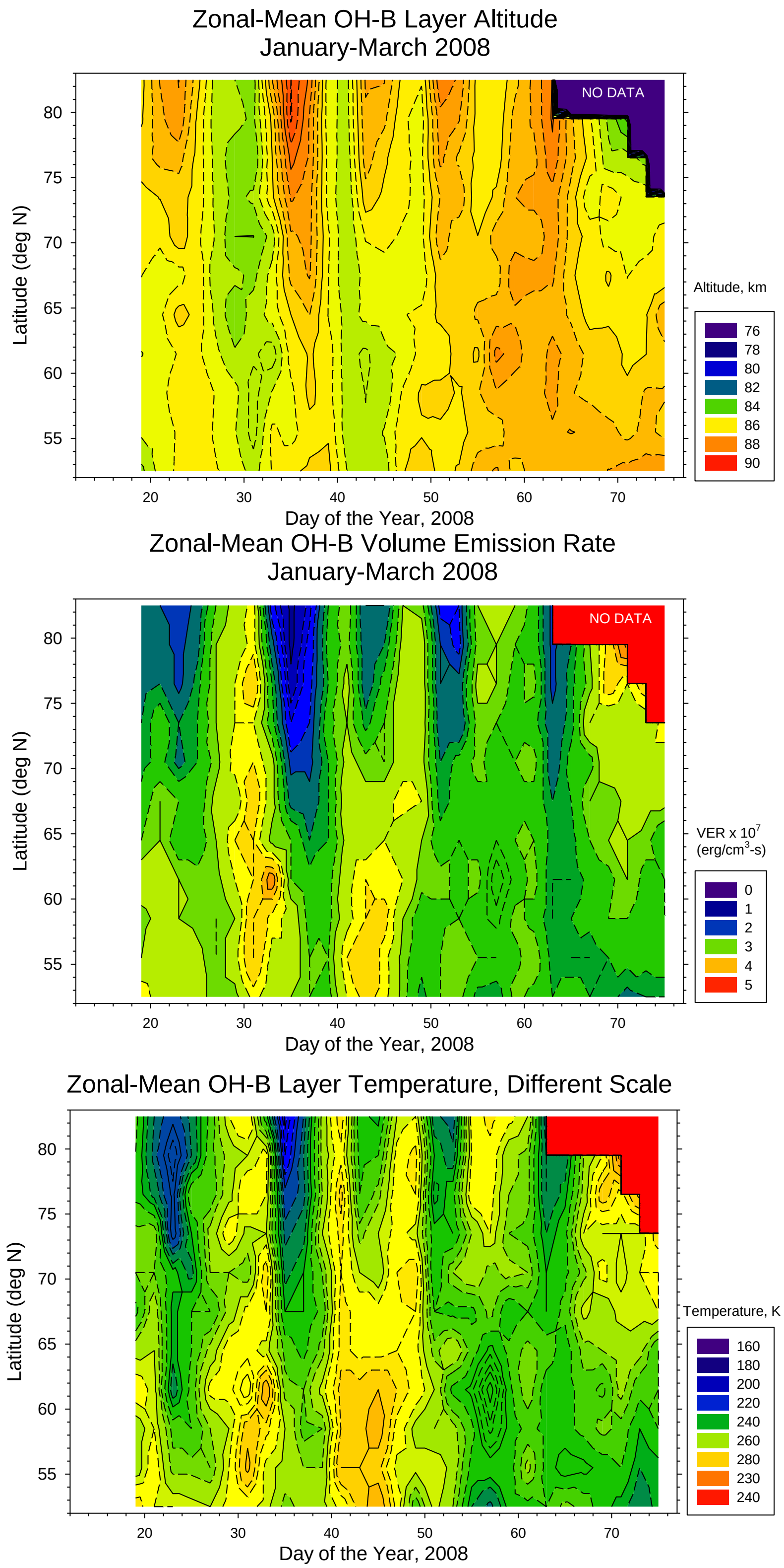

Figure 4B. As Figure 4A, but for the Winter of 2008

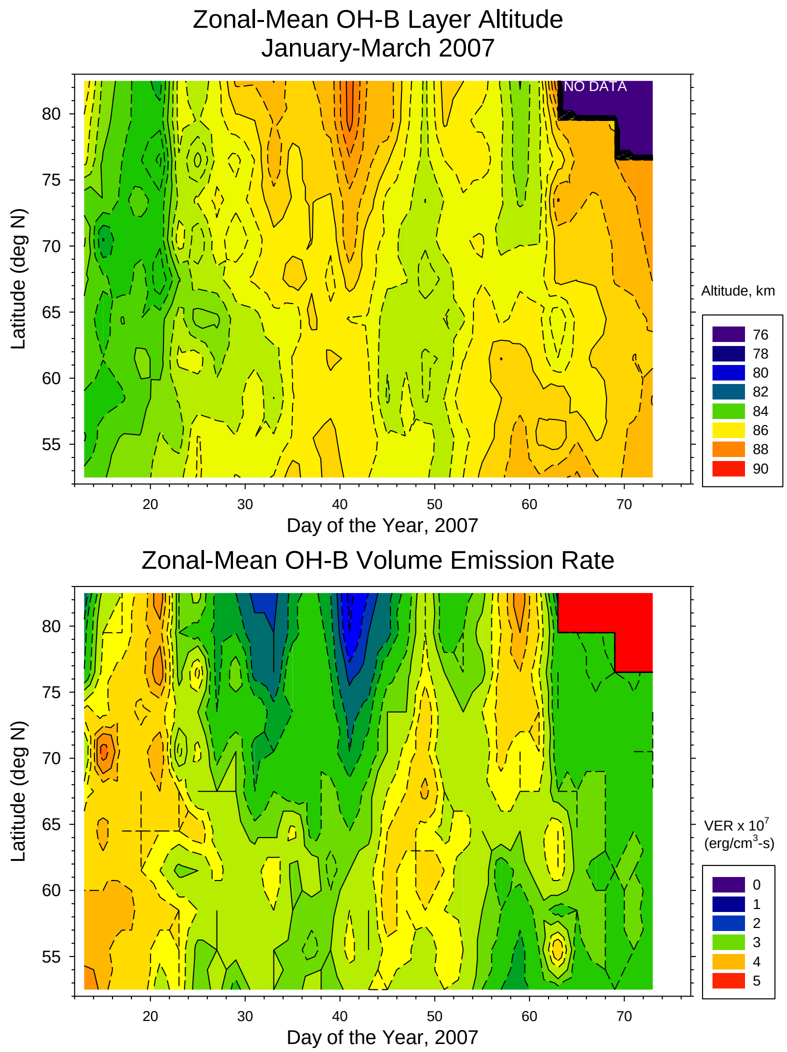

Figure 4C. As Figure 4A, but for the Winter of 2007 Layer Temperature was not Calculated

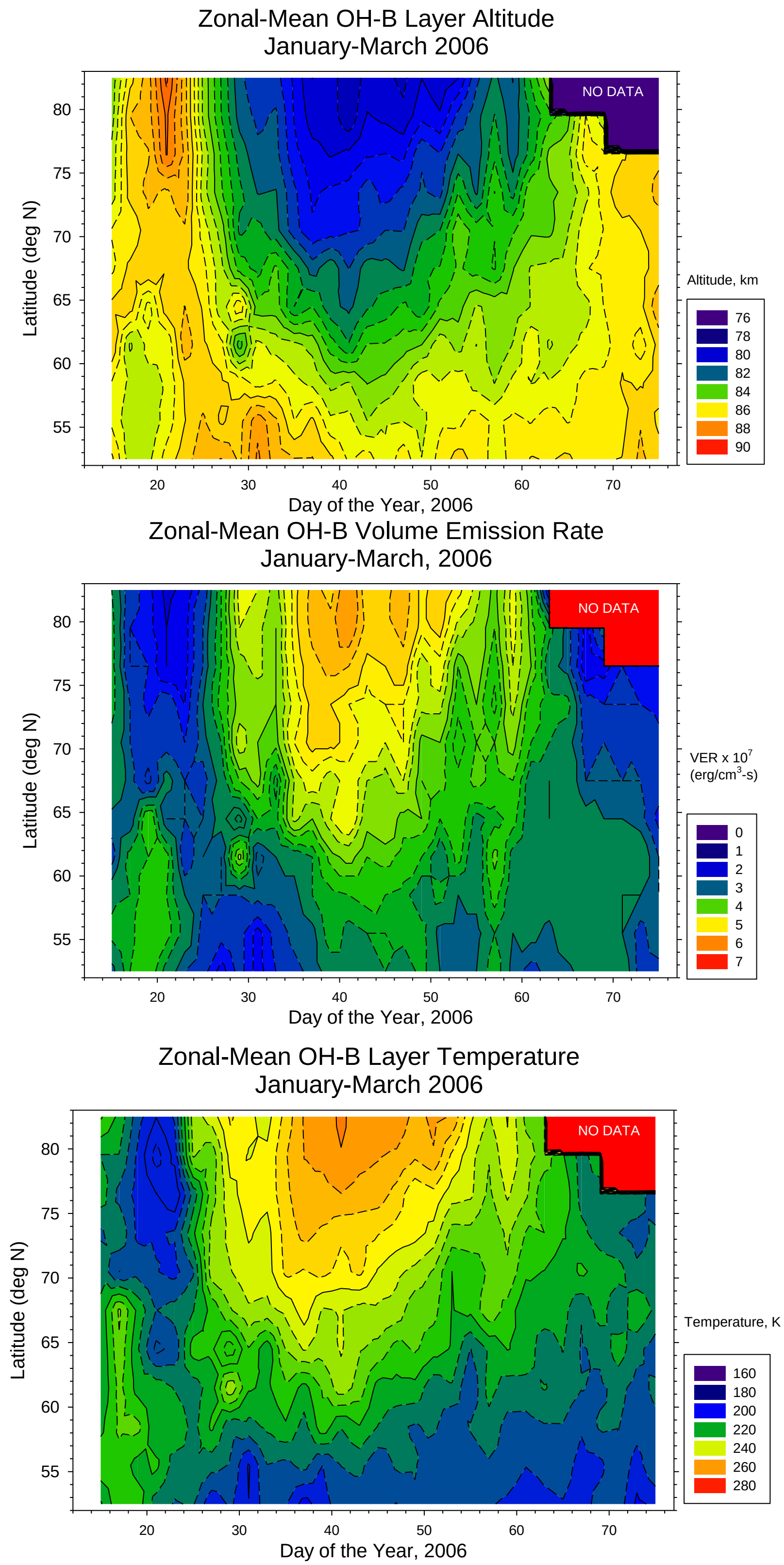

Figure 4D. As Figure 4A, but for the Winter of 2006

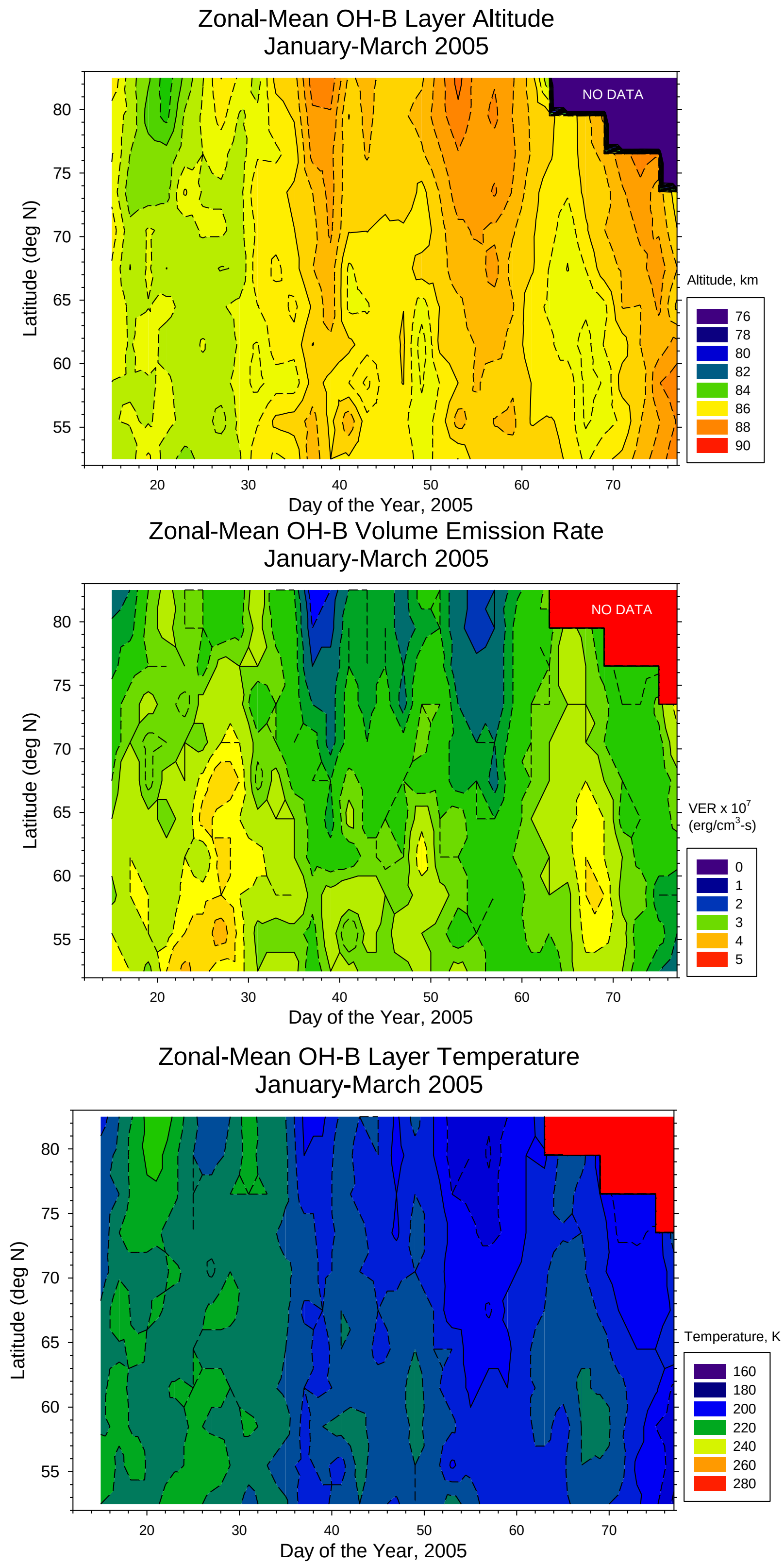

Figure 4E. As Figure 4A, but for the Winter of 2005

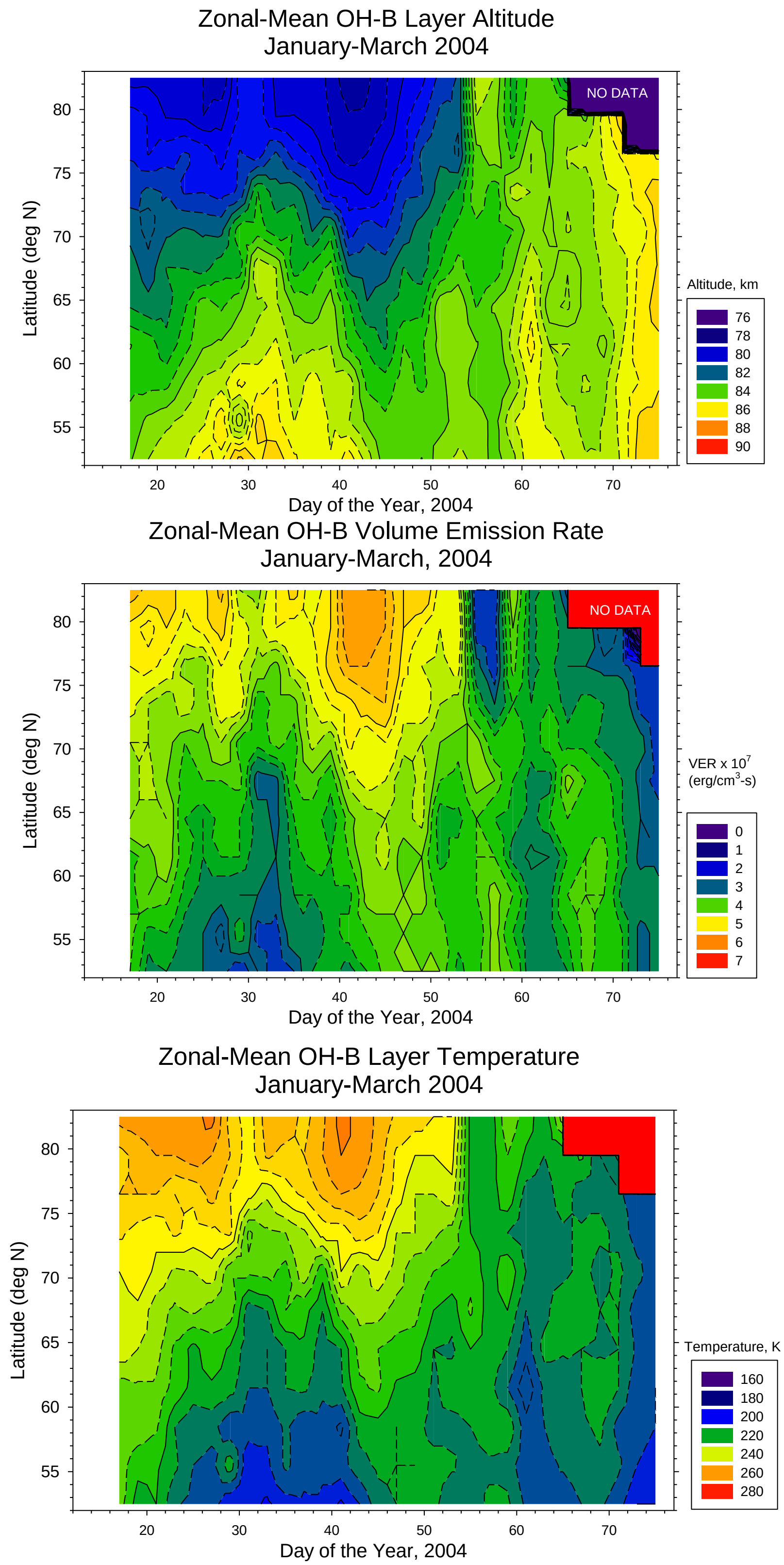

Figure 4F. As Figure 4A, but for the Winter of 2004

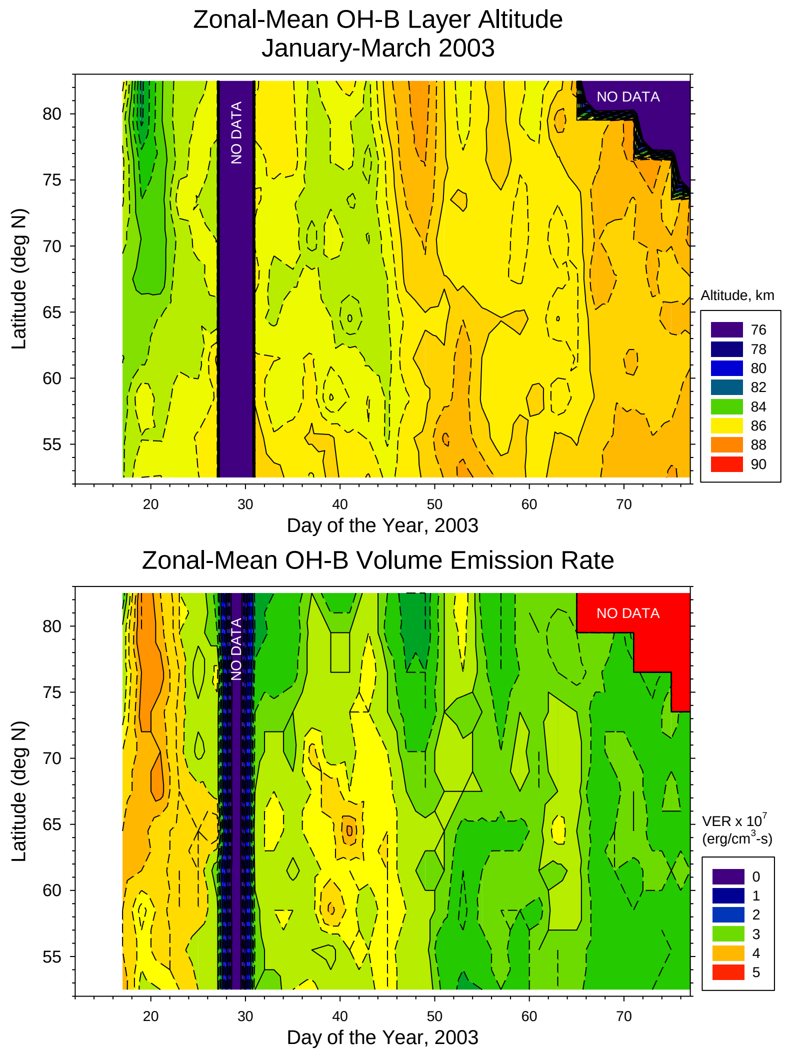

Figure 4G. As Figure 4C but for the Winter of 2003

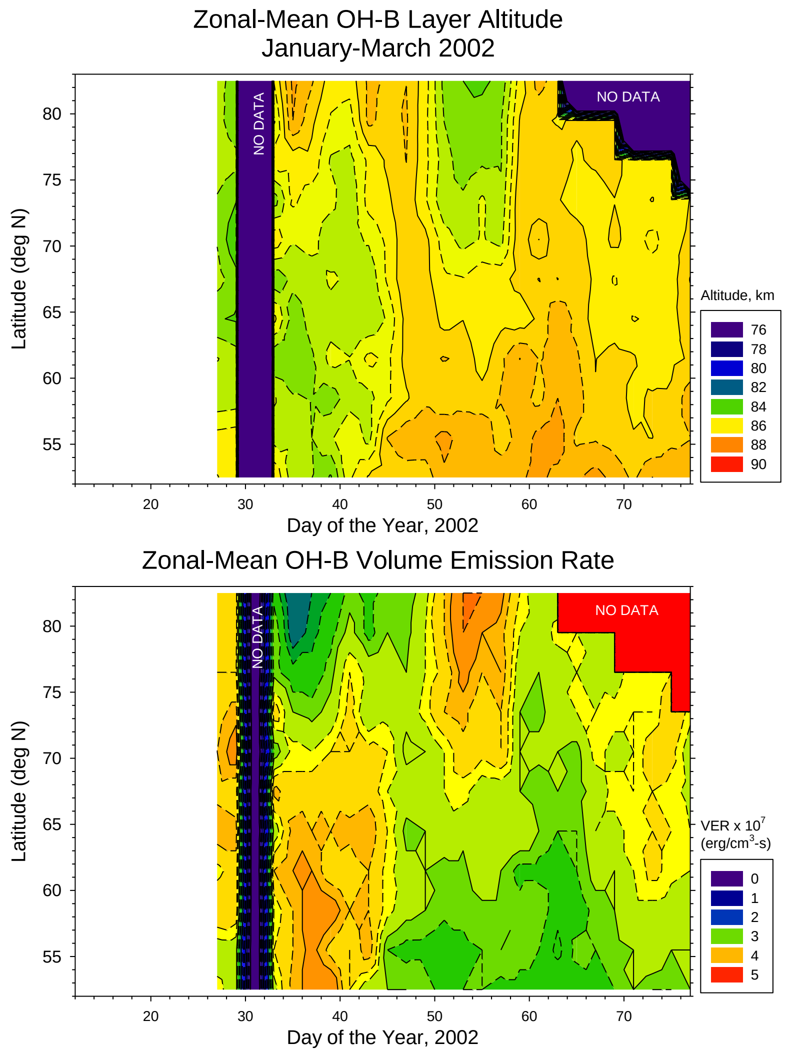

Figure 4H. As Figure 4C, but for the Winter of 2002

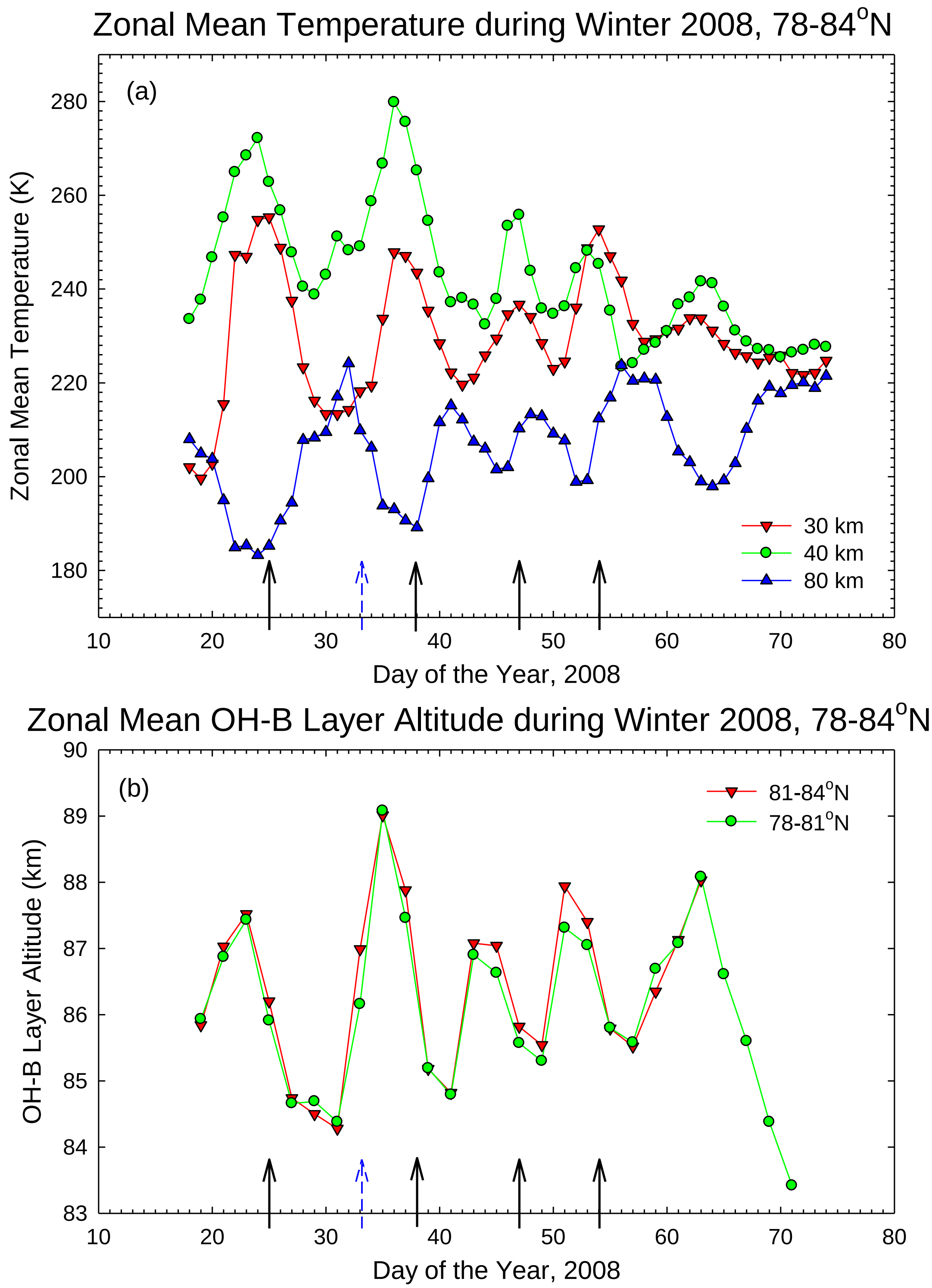

Figure 5. Variation of Zonal Mean Temperature at Three Altitudes (a), and OH Layer Altitude (b), 2008

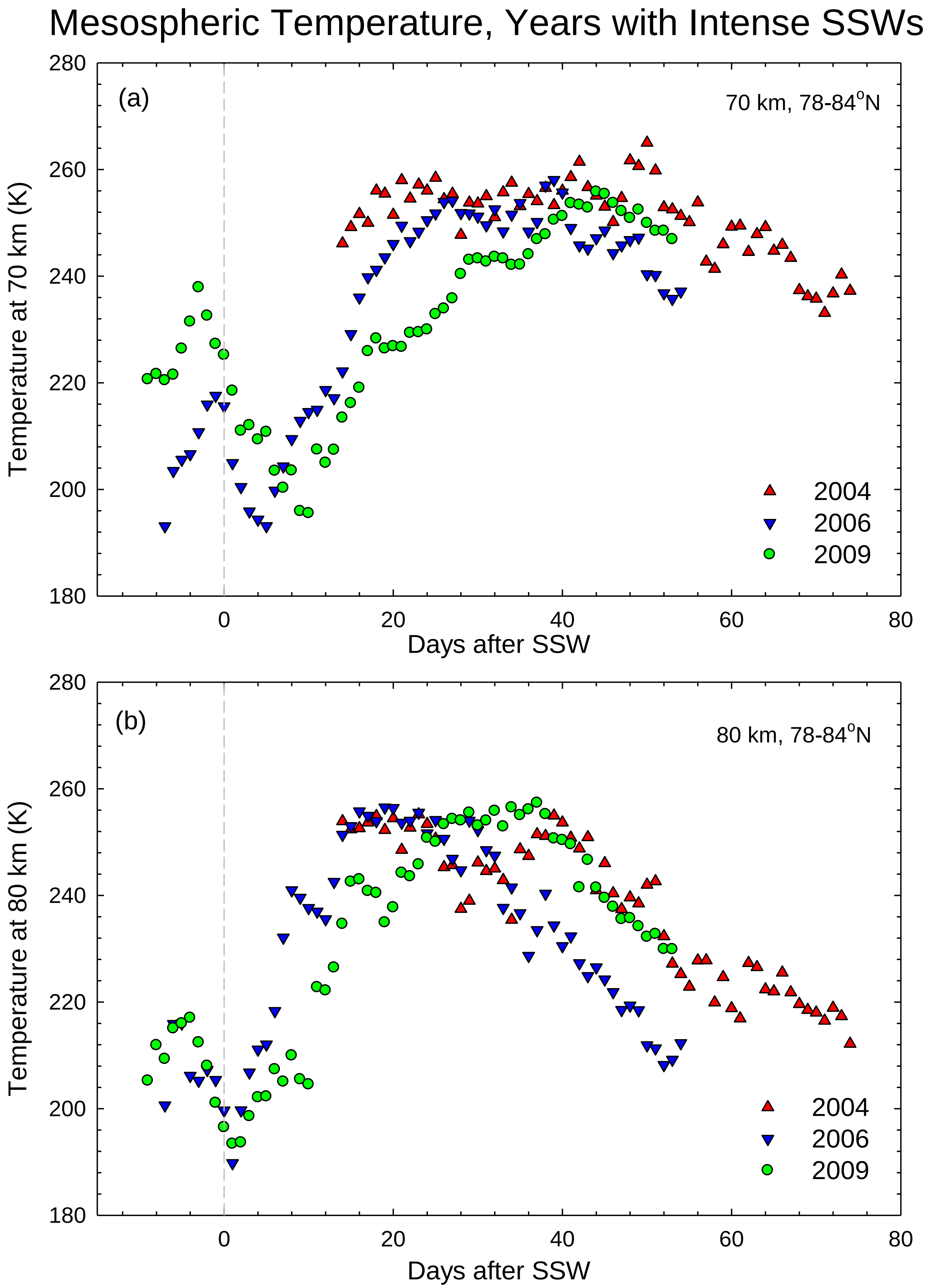

Figure 6. Cooling at (a) 70 km and (b) 80 km, Referenced to SSW Dates in 2004, 2006, and 2009

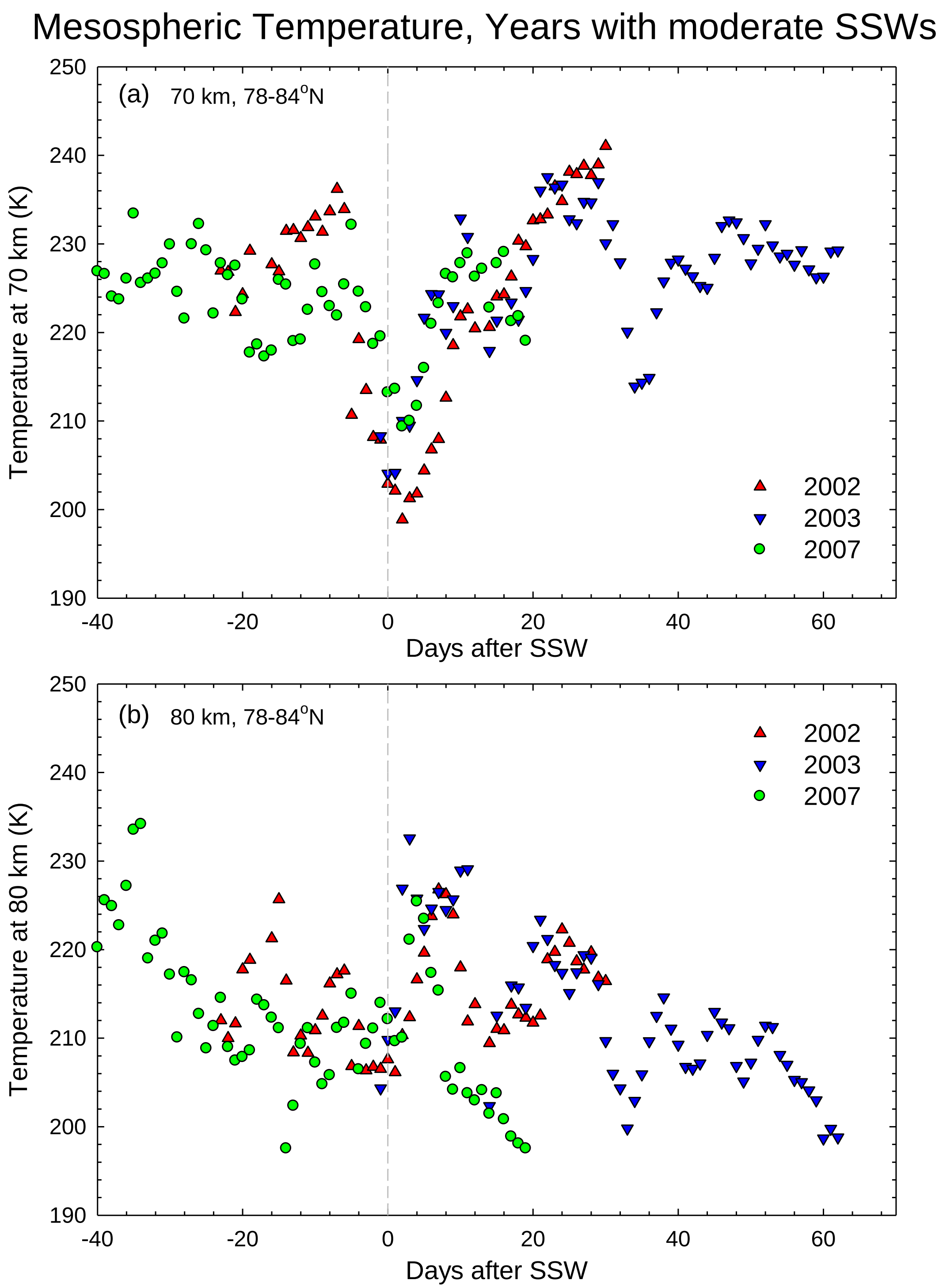

Figure 7. As Figure 6, but for the Moderate-SSW years of 2002, 2003, and 2007

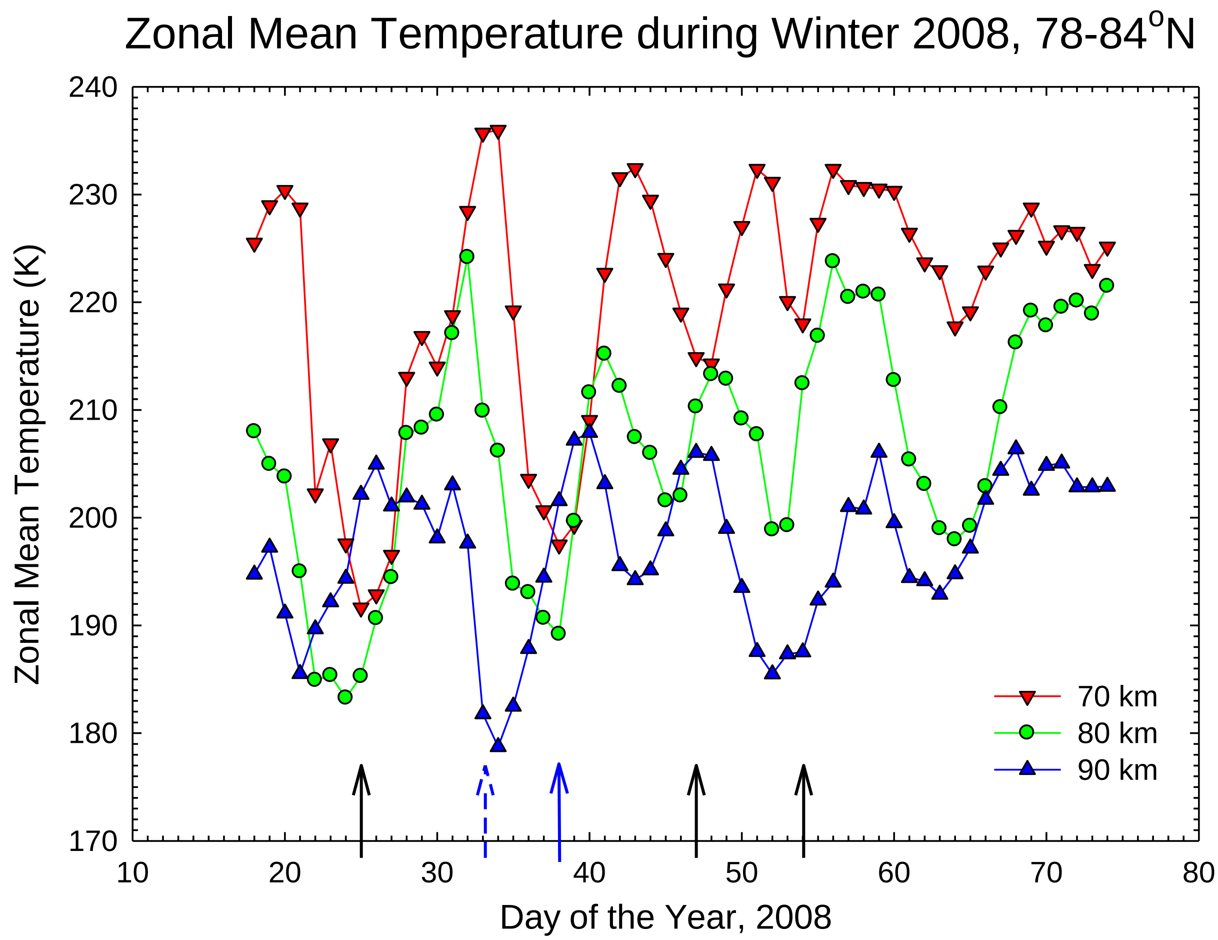

Figure 8. Variations of Zonal Mean Temperature at Three Levels in the Mesosphere During 2008, for 78-84°N

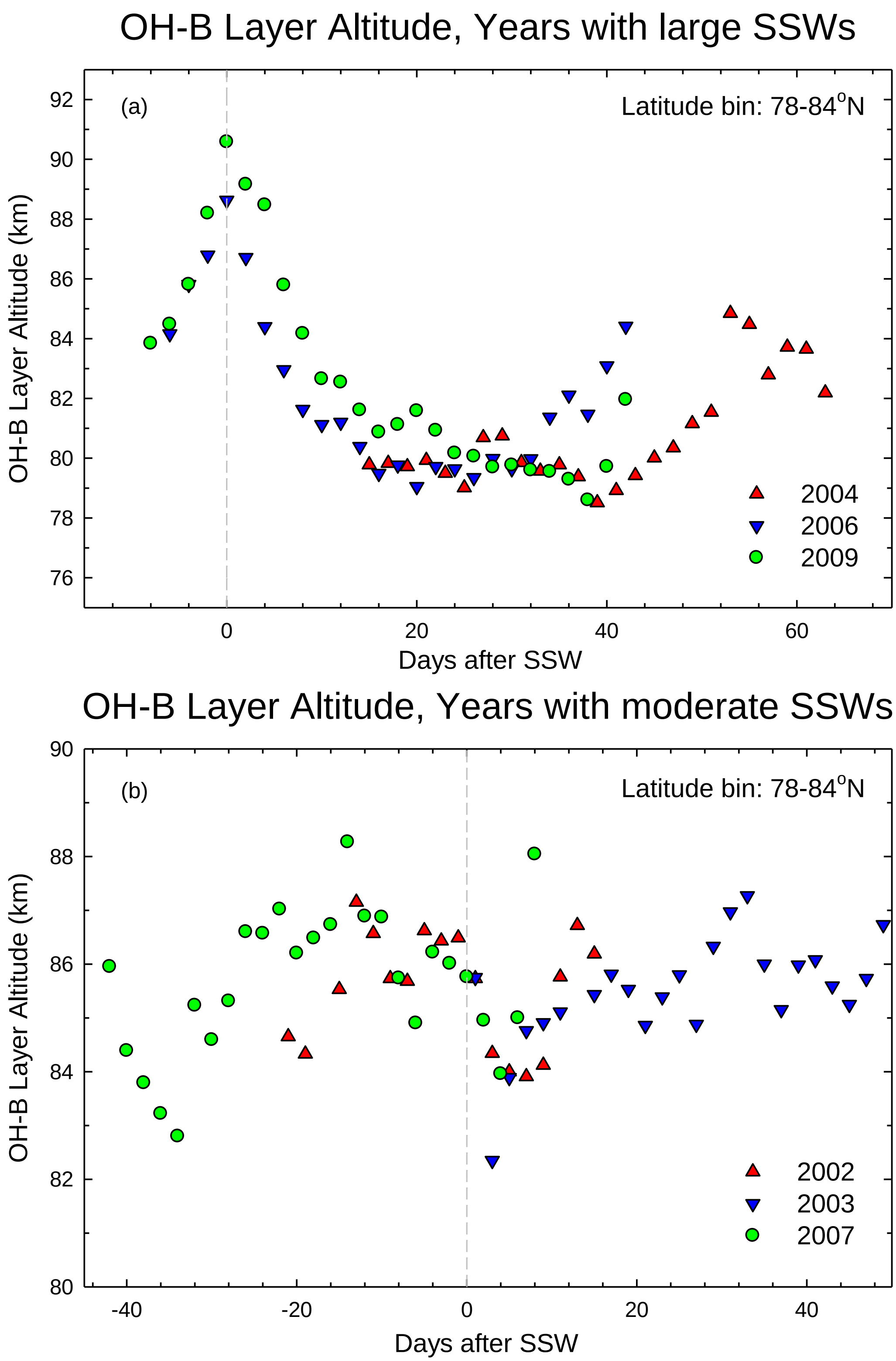

Figure 9. Variation of the OH Layer Altitude in (a) "Strong" and (b) "Moderate" Years. Note Different Altitude Ranges.

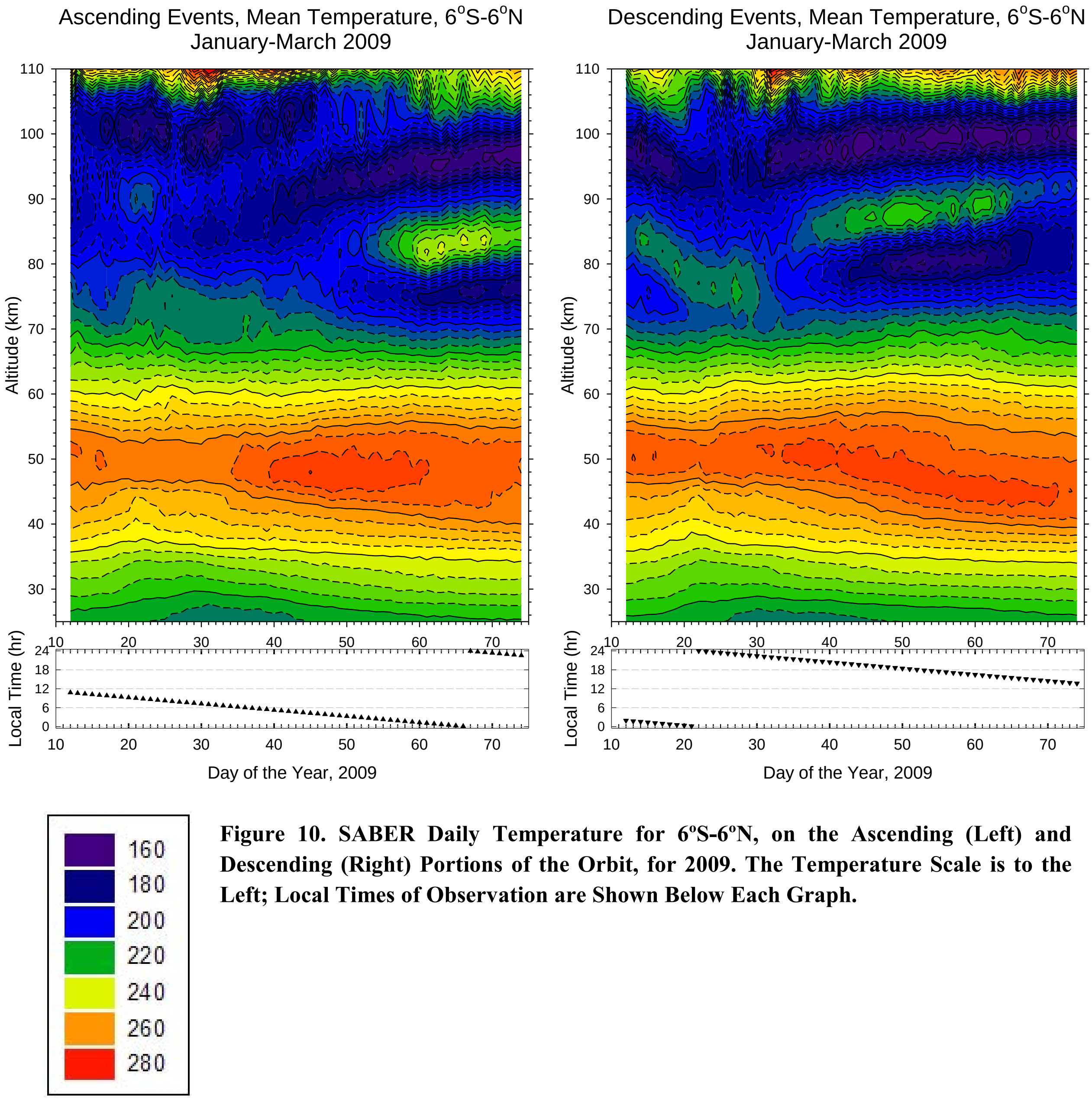

Figure 10. SABER Daily Temperature for 6ºS-6ºN, on the Ascending (Left) and Descending (Right) Portions of the Orbit, for 2009. The Temperature Scale is to the Left; Local Times of Observation are Shown Below Each Graph.

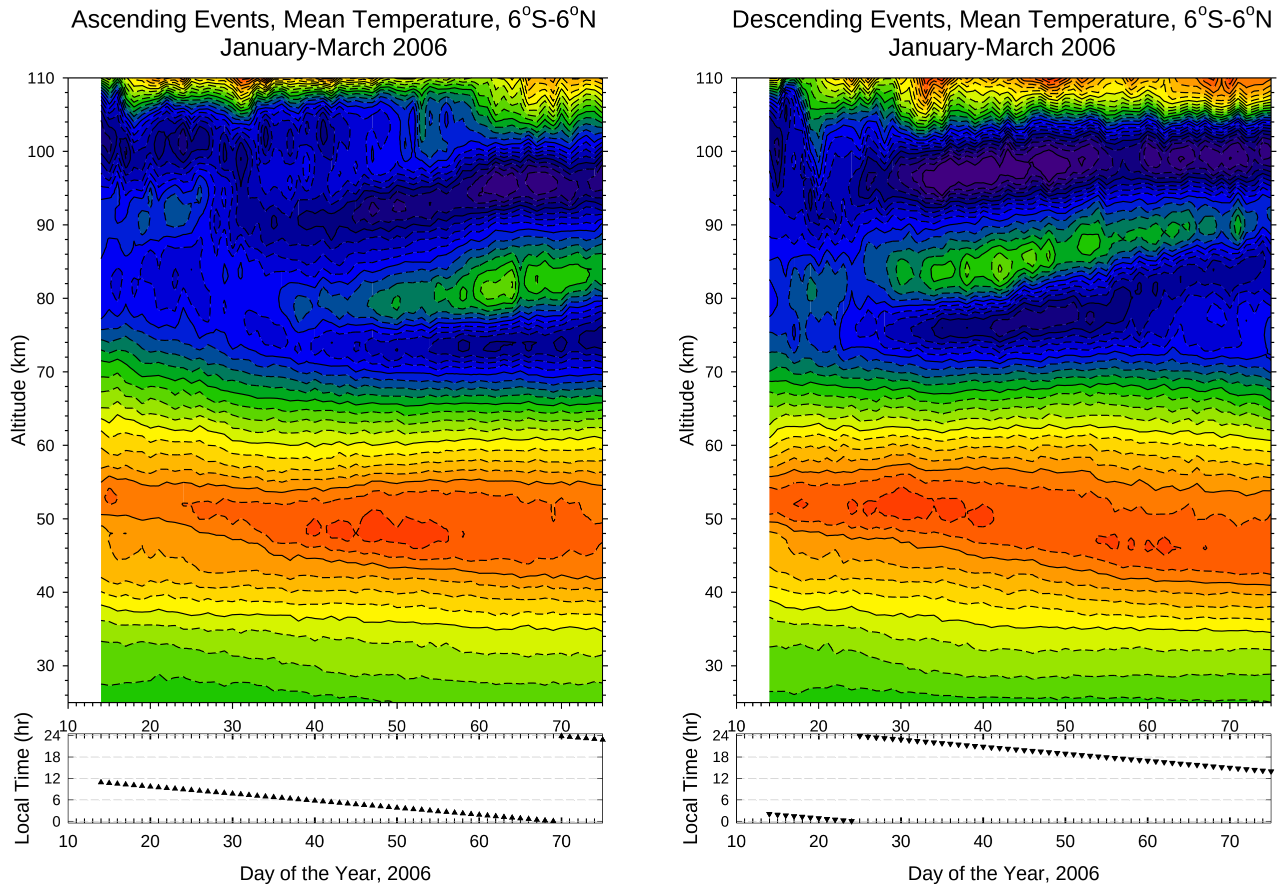

Figure 11. As Figure 10, but for 2006. The Color Scale is Also the Same.

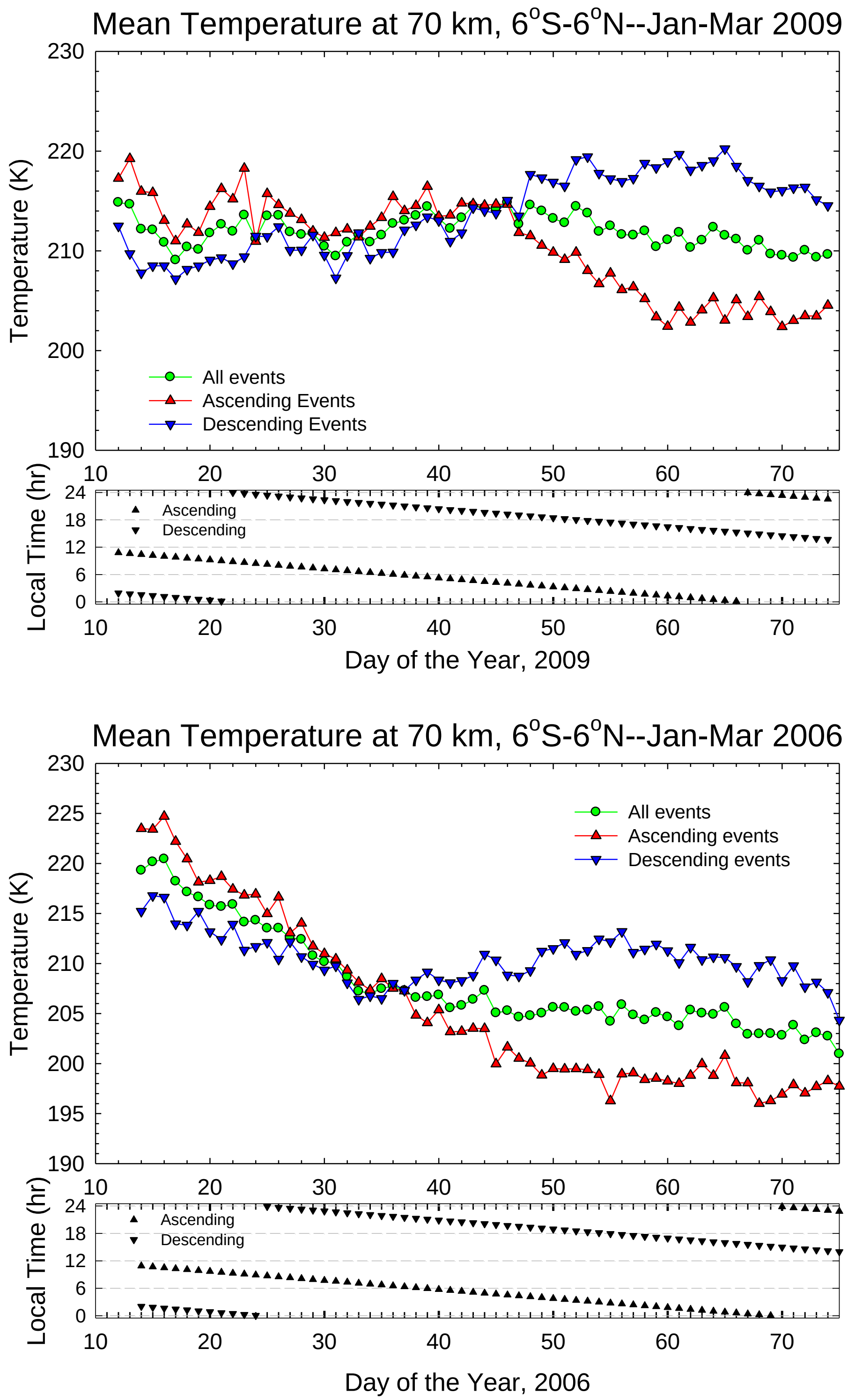

Figure 12. Variations of Daily Zonal Mean Temperature at 70 km Near The Equator, for the Years (Top) 2009 and (Bottom) 2006

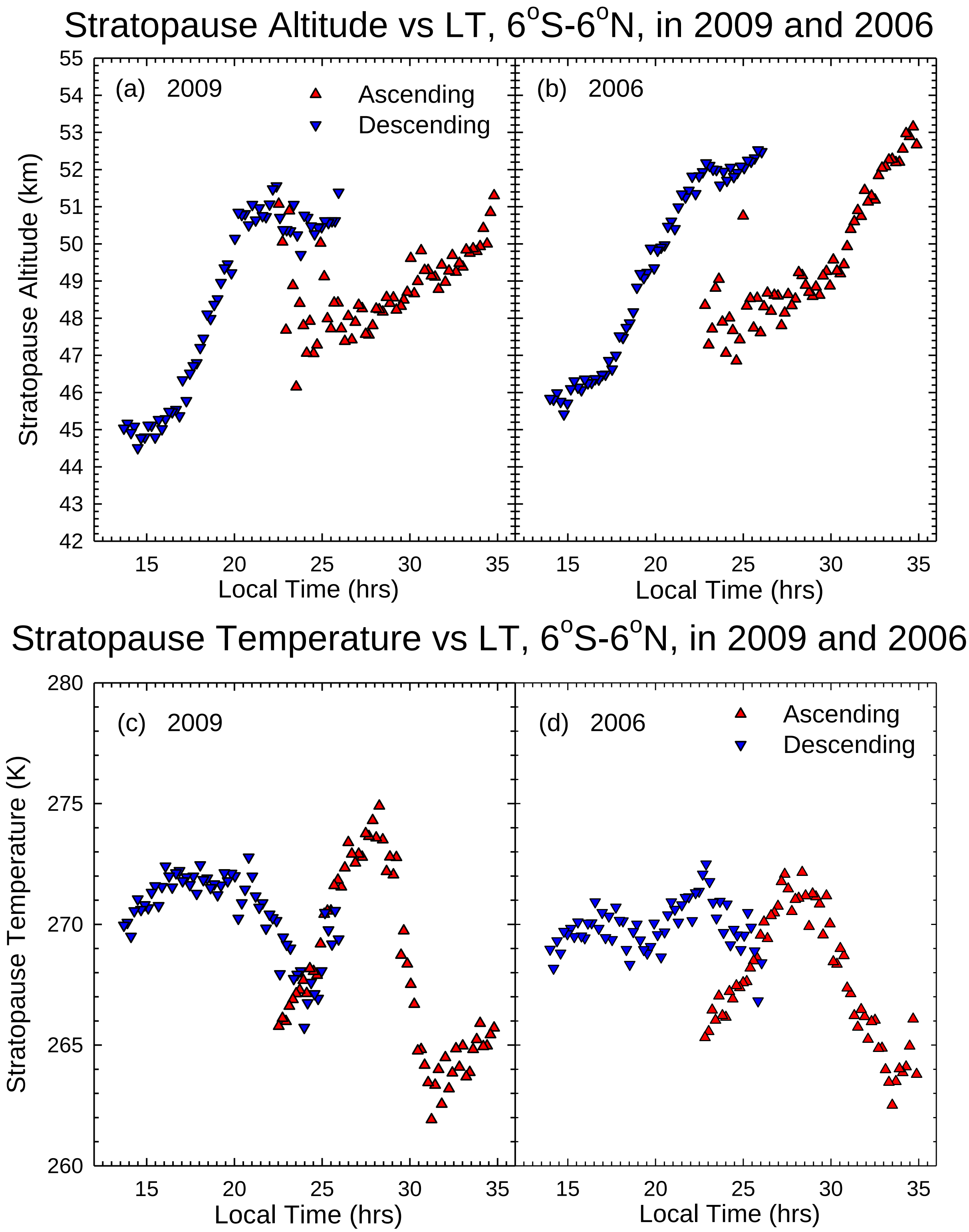

Figure 13. Equatorial Stratopause Altitude in (a) 2009 and (b) 2006; and Temperature in (c) 2009 and (d) 2006 See Text

Table 1. Stratospheric Sudden Warmings Since 2002

Date	DOY	Strength	QBO	F10.7a	Reference	Comment
~17 February 2002	48	Major	E	220	[44]	Short duration
~16 January 2003	16	Major	W	150	[44]	
~19 February 2003	50	Minor	W	143	[44]	"nearly major"
~5-6 March 2003	64-65	Minor	W	137	[44]	"nearly major"
2-3 January 2004	2-3	Major	E	136	[44]	Intense event
20 January 2006	20	Major	E	85	[46]	Intense event
February 2007		Major	W	80	[41]	
25 January 2008	25	Minor	E	73	[42]	Large warming, no wind reversal
2 February 2008	33	Minor	E	73	[42]	Questionable date; see text
16 February 2008	47	Minor	E	72	[42]	
23 February 2008	55	Major	E	72	[42]	
21 January 2009	21	Major	W	66	[35]	Intense event

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